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Article

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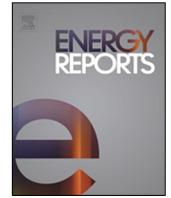
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Research paper

GA-based optimization for optimally placed and properly coordinated control of distributed generations and Static Var Compensator in distribution networks



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ABSTRACT

This paper presents the impact assessment of distributed generations (DGs) (such as T_2 and T_4 i.e. operating at different power factors such as 0.85, 0.90, 0.95 and 0.99 leading and lagging, respectively) and flexible alternating current transmission systems (FACTS) controllers like SVC with different load models (DLMs) in distribution power system networks by using genetic algorithms (GA) from minimum total MVA intake of main substation viewpoint. The different type DGs (such as T_2 and T_4 i.e. operating at different power factors such as 0.85, 0.90, 0.95 and 0.99 leading and lagging, respectively) and FACTS controller like SVC with DLMs are considered by employing GA in DPSs form minimum total MVA intake of main substation viewpoint. Different distribution power system (DPS) performance indices viewpoint, such as minimization of real power loss, minimization of reactive power loss, improvement of voltage profile, reduce the short circuit current or MVA line capacity and reduce the environmental greenhouse gases like carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxide (NO_x) and particulate matters in an emergency e.g. under fault, sudden change in field excitation of alternators or load increase in DPSs are considered. This paper also investigated the comparisons of different DGs (such as T_2 and T_4) and FACTS controller like SVC with DLMs by employing GA in DPSs form minimum total MVA intake of main substation viewpoint. The effectiveness of the proposed methodology is tested on IEEE 37-bus distribution test system. All the simulations are done on MATLAB package toolbox.

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1. Introduction

In the DPSs, the various emergency conditions such sudden load change, sudden fault occurs on system, and sudden change in field excitation of alternators are cause of power system instability such voltage instability, frequency instability and rotor angle instability. In such emergency conditions basically RLP and RP are shortage in DPSs. This can be overcome by integration of DGs and FACTS controllers in systems since such devices are feeding RLP as well as RP to the system in emergency conditions of systems. So that the integration of DG and FACTS controllers in system is important issues. From last two decades a lot of researchers are doing work on integrations of DG as well as FACTS controllers in system from different DPSs performance viewpoints.

The integration of DGs and FACTS controllers in DPSs from different DPSs performance indices are better achieved. So that

the optimal placement and size of DGs and FACTS controllers in DPSs are important issues for better DPS performance such as minimization of RLP and RP losses, improvement of voltage profile of system buses, minimization of short circuit current or MVA capacity of line, and minimization of environmental pollutions GHG emissions etc. In this thesis considered the two issues for analysis such as optimal placement and size of DGs and FACTS controllers in DPSs by GA from minimum total real power loss of the system and minimum total MVA intake of main substation viewpoints.

Ochoa et al. (2006) have proposed various indices to evaluate the impact of DG in DPSs. The indices to measure the impacts of DG introduction on loss reduction, voltage profile, current carrying capacity of conductors, and short circuit currents for three-phase and single-phase ground faults were proposed. Finally, a multi-objective function is derived for such planning studies. There are many approaches for deciding the penetration level of DG in DPSs. Hong and Ho (2005) have proposed a method based on GA to determine the network configuration. The method, formulated as a fuzzy multi-objective problem, takes

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Nomenclature

Abbreviation

CON–INS–RES– COM–REF	Constant–industrial–residential– commercial–reference load models respectively
DLMs	Different load models
EIRI	Environment impact reduction index
FACTS	Flexible alternating current transmis- sion system controllers
lg, ld	Lagging and leading operating power factors of DGs
PLI, QLI	RLP and RP index, respectively
RLP, RP	Real and reactive power, respectively
RLPM, RPM	RLP and RP multiplier, respectively
SVC	Static Var Compensator
SCCI	Short circuit current or MVA line capac- ity index
VDI	Voltage deviation index
WODG, WDG	Without DG and with DG, respectively

Symbols

LOC_{DG}	Location of DG
P_{DG}, Q_{DG}	Real and reactive power delivered by DG, respectively
P_{Lmin}, Q_{Lmin}	Minimum RLP and RP losses, respec- tively
P_{intake}, Q_{intake}	RLP and RP intake of main substation, respectively
PF_{DG}	Power factor of DG
S_{intake}	Total MVA intake of main substation
S_{system}	Total MVA of system
$SVC_{\alpha}(\alpha)$	Firing angle of SVC
SVC_{MVAR}	Reactive power of SVC
SVC_{LOC}	Location of SVC
V_{max}	Maximum value of bus voltage in p.u. (1.03)
V_{min}	Minimum value of bus voltage in p.u. (0.95)
T_1, T_2, T_3 and T_4	Different types of DGs such as DG-1, DG-2, DG-3 and DG-4, respectively
α, β	RLP and RP exponent values, respec- tively

both normal condition and the contingencies (faults) into account. The switch statuses are considered as preventive controls for multiple individual balanced faults. The statuses of both sectionalizing and tie switches are determined, while the constraints for both voltage magnitudes and line flows are satisfied. [Krishnan \(2015\)](#) has been presented the modeling of intelligent energy control center (ECC) controlling DGs using multi-agent system. Multi-agent system has been proposed to provide intelligent energy control and management in grids because of their benefits of extensibility, autonomy, reduced maintenance, etc. The multi-agent system constituting the smart grid and agents such as user agent, control agent, database agent, distributed energy resources (DER) agent work in collaboration to perform assigned tasks. The wind power generator connected with local load, the solar power connected with local load and the ECC controlled by fuzzy logic controller (FLC) are simulated in MATLAB/SIMULINK. Recently,

integration of DG in DPSs has increased to high penetration levels. The impact of DG units on the voltage stability margins has become significant. [Al Abri et al. \(2013\)](#) have proposed an optimization technique such as GA based tools which can be used to locate and size the DG units in the system, so as to utilize these units optimally within certain limits and constraints. Thus, the impacts of DG units issues, such as voltage stability and voltage profile, can be analyzed effectively in [Al Abri et al. \(2013\)](#). An improved non-dominated sorting GA-II (INSGA-II) has been proposed for optimal planning of multiple DG units by [Sheng et al. \(2015\)](#). First, multi-objective functions that take minimum line loss, minimum voltage deviation, and maximal voltage stability margin into consideration have been formed in [Sheng et al. \(2015\)](#). A hybrid GA and FL goal programming was proposed for ODGP for improvement of voltage profile in Ref. [Kim et al. \(2008\)](#).

[Akram et al. \(2015\)](#) have been presented, a new multi-agent control system (MACS) is proposed for smart distribution networks. It can: (1) eliminate the feeders' congestion, (2) globally correct voltage violations, and (3) coordinate the operation of reactive power control devices. In performing its functions, the MACS must prevent overstress on the substation voltage regulator tap changer under all operating conditions, and avoid selective active power curtailment from DG units. This can help to improve reliability, economic revenue, and power quality. A fuzzy rule-based system is employed for decision-making support in MACS. The proposed MACS can achieve the self-healing requirement of smart distribution network. It eliminates feeders' congestion by properly reconfiguring the distribution network. Meanwhile, it amends most of voltage violation problems by coordinated operation of voltage control devices in the distribution system. The MACS overcomes the severe voltage violation problems via distribution network reconfiguration. A combined GA and Tabu search (TS) was suggested by Gandomkat et al. in [Gandomkar et al. \(2005\)](#) for ODGP from real and reactive power losses viewpoint. A hybrid GA and immune algorithm were applied to solve an ODGP in [Soroudi and Ehsan \(2011\)](#) that maximizes the profit of the DNO. GA was employed to solve a weighted multi-objective ODGP model from PS performances viewpoint in Ref. [Ela et al. \(2010\)](#). [Wei et al. \(2014\)](#) have been discussed the usage of remote signals obtained from a wide-area measurement system (WAMS) introduces time delays to a wide-area damping controller (WADC), which would degrade system damping and even cause system instability. The time-delay margin is defined as the maximum time delay under which a closed-loop system can remain stable. In this paper, the delay margin is introduced as an additional performance index for the synthesis of classical WADCs for flexible ac transmission systems (FACTS) devices to damp inter-area oscillations. The proposed approach includes three parts: a geometric measure approach for selecting feedback remote signals, a residue method for designing phase-compensation parameters, and a Lyapunov stability criterion and linear matrix inequalities (LMI) for calculating the delay margin and determining the gain of the WADC based on a tradeoff between damping performance and delay margin. [Sharma et al. \(2003\)](#) have been discussed, a new method called the extended voltage phasors approach (EVPA) is proposed for placement of FACTS controllers in power systems. While the voltage phasors approach (VPA) identifies only the critical paths from the voltage stability viewpoint, the proposed method additionally locates the critical buses/line segments. The results of EVPA are compared with the well-established line flow index (LFI) method for nine-bus, 39-bus, and 68-bus systems. It is shown that the EVPA provides accurate indication for the placement of FACTS controllers. [Chris et al. \(2015\)](#), Installed capacities of distributed generation (DG) are projected to increase substantially in Great Britain and many other power systems. This paper will discuss the definition of capacity value of DG

arising from its ability to support additional demand without the need for new network capacity, in analogy with the definition of effective load carrying capability (ELCC) at transmission level. This calculated ELCC depends on the precise detail of its definition; in particular in a demand group fed by a pair of circuits where the double outage state dominates the calculated reliability index, the ELCC will be very small unless the generator can run in islanded mode. Miranda et al. (1994) have described a GA approach to the optimal multistage planning of the distribution networks. In this work a mathematical and algorithmic models are developed and experimented with real systems. The advantages of adopting this new approach are in planning context, in conjunction with adoption of multi-criteria decision making methods. GA-FL based optimal placement of DG was discussed by Akorede et al. in Akorede et al. (2011) considering multi-objective functions including system losses, system loading as well as the profit for DISCOs.

Sebastian et al. (2015), have been presented a without appropriate counteraction, the high amount of installed distributed generators (DG) at the low-voltage distribution level may cause overloading of electrical equipments and violation of voltage limits in many grids. Because of the historically grown low-voltage grids and their local and geographic dependencies, complex grid structures can be found. Thus, the discrimination of grids concerning their DG capacity is a difficult task. In Mohammadi et al. (2012), GA-based optimal sizing of micro-grid and DG units under pool and hybrid electricity markets was presented. Hadi and Majid (2012) have adopted a straight forward approach, such as GA, to minimize unsupplied energy and power loss through DG placement and evaluating PQ in relation to load variations over time. A combined fuzzy logic (FL) and GA were used in an ODGP model that minimizes the cost of real power (RLP) loss (Kim et al., 2002). A combined FL and GA were employed to solve a weighted multi-objective ODGP model for different PS performance indices viewpoint in Ref. Akorede et al. (2011) and Vinothkumar and Selvan (2011). Multi-objective optimization for DG planning with load models is presented in Singh et al. (2009), Aziz et al. (2013), Claudio and Faur (1999) and Chiradeja and Ramakumar (2004). Aziz et al. (2013) have been discussed a wide-scale penetration of distributed-generation (DG) units into a weakly meshed distribution system is one of the major concerns for power system engineers in recent years. As grid standards limit voltage control operation of small DG units, a lack of sufficient reactive power support brings the problem of slow voltage recovery and this leads to the usage of expensive flexible ac transmission system (FACTS) devices, such as a static synchronous compensator (STATCOM). In this paper, a systematic methodology has been developed for fast voltage recovery at the DG bus. This methodology reduces the number as well as the rating of STATCOMs through the tuning of control parameters.

The concept of optimal placement and properly coordinated control of DGs and FACTS controllers are discussed in open literature. The schematic diagram of interaction between DGs and FACTS controllers is shown in Fig. 1. The frequency ranges of interactions between different types of DG and FACTS controllers are given in Table 1.

In this paper, the power flow solutions for the 38-node distribution test system are obtained in the following fashion. Different types of DGs size are considered in a practical range (0–4.00 p.u), decided by the total system demand which is 3.9093 p.u. The DG of 0.0 p.u. corresponds to system without DG whereas 4.00 p.u corresponds to a case when all the real power requirements are met by DG. It is considered that the DG is operated at unity p.f. Each bus of the system is considered for the placement of DG of given size from the range considered. The size of SVC are considered in a practical range (–0.500 to +0.500 p.u). The bus voltages occurring outside the range 0.95–1.03 p.u. are treated as voltage violation.

The various open literatures are used for introduction (Ochoa et al., 2006; Hong and Ho, 2005; Krishnan, 2015; Al Abri et al., 2013; Sheng et al., 2015; Kim et al., 2008; Akram et al., 2015; Gandomkar et al., 2005; Soroudi and Ehsan, 2011; Ela et al., 2010; Wei et al., 2014; Sharma et al., 2003; Chris et al., 2015; Miranda et al., 1994; Akorede et al., 2011; Sebastian et al., 2015; Mohammadi et al., 2012; Hadi and Majid, 2012; Kim et al., 2002; Akorede et al., 2011; Vinothkumar and Selvan, 2011; Singh et al., 2009; Aziz et al., 2013), mathematical problem formulations (Ochoa et al., 2006; Hong and Ho, 2005; Krishnan, 2015; Al Abri et al., 2013; Sheng et al., 2015; Kim et al., 2008; Akram et al., 2015; Gandomkar et al., 2005; Soroudi and Ehsan, 2011; Ela et al., 2010; Wei et al., 2014; Sharma et al., 2003; Chris et al., 2015; Miranda et al., 1994; Akorede et al., 2011; Sebastian et al., 2015; Mohammadi et al., 2012; Hadi and Majid, 2012; Kim et al., 2002; Akorede et al., 2011; Vinothkumar and Selvan, 2011; Singh et al., 2009; Aziz et al., 2013; Claudio and Faur, 1999; Chiradeja and Ramakumar, 2004), static load models (Singh et al., 2009), impacts of DG and FACTS controllers like SVC on PS and its impact assessments issues (Aziz et al., 2013; Claudio and Faur, 1999).

1.1. Motivation of the present work

Literature survey (Singh et al., 2009), cited in the present work, are pertaining to the impact assessment of DPS performance indices with single type of DG having different loading conditions such as static load models by applying different novel approaches such as GA (Singh et al., 2009) and exhaustive search approach such as deterministic approach (Vinothkumar and Selvan, 2011). Literature review reveals that the investigation of performance indices of DPS having DGs (such as T_2 and T_4) and FACTS controllers like SVC with DLMS has not been used in the open literatures. Literature survey also reveals that the investigation of performance indices of DPS having same kind of DG (such as T_2 and T_4 at different operating PFs) and FACTS controllers like SVC with DLMS offer better DPS indices when PFs varies from 0.80 to 0.99 leading and lagging, respectively and this is not published in any journals.

1.2. Contribution of the paper

This paper considers DGs (such as T_2 and T_4 are operating at different PFs i.e. varies from 0.80 to 0.99 leading and lagging, respectively) and FACTS controllers like SVC with DLMS for impact assessment of DPS performance indices from minimum total MVA intake of main substation viewpoint by using GA. This paper also clarifies the fact that, among the four types of DGs considered, T_2 and T_4 type DGs at different operating PFs and FACTS controllers like SVC with DLMS offer better DPS performance indices when PFs varies from 0.80 to 0.99 leading and lagging, PFs respectively.

1.3. Organization of the paper

The organization of the rest of the paper is as follows: The next Section 2 discusses the mathematical problem formulation. Section 3, discusses the GA implementation. Section 4, discusses the multi-objective function based formulation. In Section 5, simulation results and discussions are focused. Finally, the conclusions of the present paper and future research scope are presented in Section 6.

2. Mathematical problem formulation

The different types of static load models, DG and FACTS controller like SVC model are presented in this section as follows:

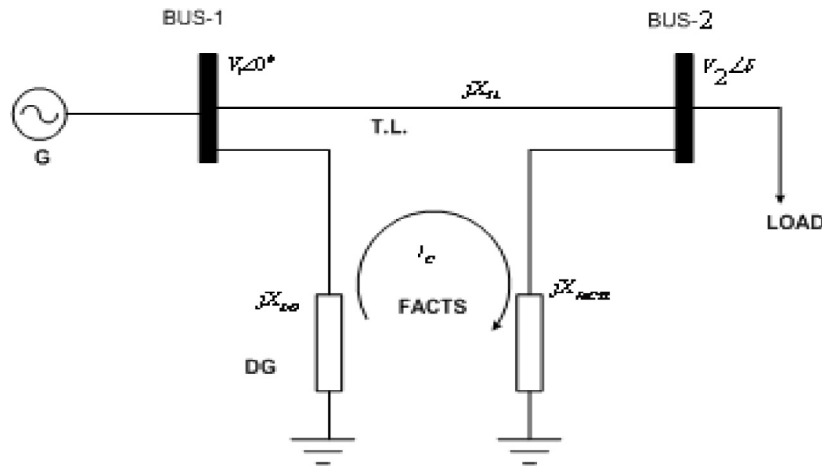


Fig. 1. Schematic diagram for optimal placement and properly coordinated control of DGs and FACTS controller in DPSs.

Table 1
Frequency ranges of interactions between different types of DG and FACTS controllers.

Sl. no.	Frequency ranges	Type of interactions between different types of DG and FACTS controllers
1	0 Hz	Steady-state interactions
2	0–3 or 5 Hz	Electro-mechanical oscillations
3	2–15 Hz	Small-signal or control oscillations
4	10–50/60 Hz	SSR interactions
5	> 15 Hz	Electro-magnetic transients, high frequency resonance or harmonic resonance interactions and network resonance interactions

Table 2
Values of relevant factors of DLMs for buses (IEEE 37-bus distribution test system).

Bus no.	A*	B*	C*	Bus no.	A*	B*	C*
1(GSP)	0.0000	0.0000	0.0000	20	0.3000	0.4000	0.3000
2	0.2000	0.5000	0.3000	21	0.3000	0.4000	0.3000
3	0.1500	0.6000	0.2500	22	0.3000	0.4000	0.3000
4	0.2000	0.5000	0.3000	23	0.3500	0.4500	0.2000
5	0.1100	0.3400	0.5500	24	0.2000	0.6500	0.1500
6	0.1500	0.3000	0.5500	25	0.2000	0.6500	0.1500
7	0.3000	0.5000	0.2000	26	0.1500	0.2000	0.6500
8	0.3000	0.5000	0.2000	27	0.1000	0.2500	0.6500
9	0.0800	0.1000	0.8200	28	0.1000	0.3000	0.6000
10	0.0800	0.2000	0.7200	29	0.2500	0.3500	0.4000
11	0.1200	0.2000	0.6800	30	0.5000	0.3500	0.1500
12	0.2500	0.3000	0.4500	31	0.2000	0.3500	0.4500
13	0.2000	0.3500	0.4500	32	0.3000	0.5500	0.1500
14	0.1500	0.3500	0.5000	33	0.2000	0.3500	0.4500
15	0.0500	0.3000	0.6500	34	0.0000	0.0000	0.0000
16	0.0800	0.1000	0.8200	35	0.0000	0.0000	0.0000
17	0.0800	0.2000	0.7200	36	0.0000	0.0000	0.0000
18	0.3000	0.4000	0.3000	37	0.0000	0.0000	0.0000
19	0.3000	0.4000	0.3000	38	0.0000	0.0000	0.0000

A* means $w_{ins_pi_bus} = w_{ins_qi_bus}$, B* means $w_{res_pi_bus} = w_{res_qi_bus}$ and C* means $w_{com_pi_bus} = w_{com_qi_bus}$.

2.1. Type of static load models

To quantify the effect of different types of DG, on DG and FACTS controllers like SVC planning (DG + SVC) for different load scenario i.e. summer day, summer night, winter day and winter night loads, an IEEE-38 bus distribution system is adopted in Singh et al. (2009). In conventional load flow analysis, the active and reactive power loads are assumed as constant power load whereas, in practice, the loads may be voltage dependent i.e. industrial, residential, and commercial loads which may be represented by models as described in Singh et al. (2009). The voltage dependent load model is a static load model that represents the power system relationship to voltage as an exponential

form and represented by Eqs. (1)–(2).

$$P_{x_bus} = P_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{alpha_{RLP}} \tag{1}$$

$$Q_{x_bus} = Q_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{beta_{RP}} \tag{2}$$

where $alpha_{RLP}$ and $beta_{RP}$ are RLP and RP exponents; P_{x_bus} , Q_{x_bus} , P_{0x_bus} , Q_{0x_bus} , V_{x_bus} , and V_{0x_bus} are in per unit. Above equations neglect the frequency dependence of distribution system load, due to the fact that it is pan-system phenomenon which cannot be controlled locally and remain same for whole of the system. In practice, the load on each bus may be the composition of

Table 3
Exponent values for DLMs (Singh et al., 2009).

Load models	α	β
CON	0.00	0.00
INS	0.18	6.00
RES	0.92	4.04
COM	1.51	3.40
REF	0.91	1.00

industrial, residential, commercial, reference load models which may vary with seasonal day and night. Therefore, in Singh et al. (2009), the seasonal mixed load model at each bus is considered and are described in Eqs. (3) and (4).

$$P_{x_bus} = w_{ins_px_bus} \cdot P_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{\alpha_{RPL_ins}} + w_{res_px_bus} \cdot P_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{\alpha_{RPL_res}} + w_{com_px_bus} \cdot P_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{\alpha_{RPL_com}} + w_{ref_px_bus} \cdot P_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{\alpha_{RPL_ref}} \quad (3)$$

$$Q_{x_bus} = w_{ins_qx_bus} \cdot Q_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{\beta_{RPL_ins}} + w_{res_qx_bus} \cdot Q_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{\beta_{RPL_res}} + w_{com_qx_bus} \cdot Q_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{\beta_{RPL_com}} + w_{ref_qx_bus} \cdot Q_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{\beta_{RPL_ref}} \quad (4)$$

where V_{x_bus} = bus voltage with DG and FACS controllers like SVC; V_{0x_bus} = nominal bus voltage without DG and FACS controllers like SVC; α_{RPL_ins} and β_{RPL_ins} are RLP and RP exponents for industrial load model, respectively; α_{RPL_res} and β_{RPL_res} are RLP and RP exponents for residential load model, respectively; α_{RPL_com} and β_{RPL_com} are RLP and RP exponents for commercial load model, respectively; α_{RPL_ref} and β_{RPL_ref} are RLP and RP exponents for reference load model, respectively; $w_{ins_px_bus}$, $w_{res_px_bus}$, $w_{com_px_bus}$, and $w_{ref_px_bus}$ are the relevant factors for RLP industrial, residential, commercial, reference load models at bus x , respectively; $w_{ins_qx_bus}$, $w_{res_qx_bus}$, $w_{com_qx_bus}$ and $w_{ref_qx_bus}$ are the relevant factors for RP industrial, residential, commercial, and reference load models at bus i , respectively. Equations (5) and (6) must be satisfied for all buses except buses without load (BWL) (bus 1 is chosen as slack bus and buses 34 to 38 are not having any load in Singh et al. (2009)).

$$w_{ins_px_bus} + w_{res_px_bus} + w_{com_px_bus} + w_{ref_px_bus} = 1 \quad \text{for } x = 1 \text{ to } N_B, \text{ but } x \neq \text{BWL} \quad (5)$$

$$w_{ins_qx_bus} + w_{res_qx_bus} + w_{com_qx_bus} + w_{ref_qx_bus} = 1 \quad \text{for } x = 1 \text{ to } N_B, \text{ but } x \neq \text{BWL} \quad (6)$$

For example, the relevant factor of each load model at each bus (hypothetically generated). In this study, it is assumed that $w_{ins_px_bus} = w_{ins_qx_bus}$, $w_{res_px_bus} = w_{res_qx_bus}$, $w_{com_px_bus} = w_{com_qx_bus}$, $w_{ref_px_bus} = w_{ref_qx_bus}$. The values of this factor are given in Table 2.

The values for exponents of voltage for active and reactive component of constant, industrial, residential, commercial, and reference load models are given in Table 3.

Table 4
Type and size of DGs.

Sl. no.	Type	Rating
1	Micro DG	1 W – 5 kw
2	Small DG	5 kW – 5 MW
3	Medium DG	5 MW – 50 MW
4	Large DG	50 MW – 300 MW

2.2. Impact assessment of DG and FACTS controllers on DPS and its impact indices

2.2.1. Mathematical modeling of DG and FACTS controllers

(a) Different types of DG: The technical issues related to DGs, however, may vary, significantly, with the rating of the DPSs. Therefore, it would be appropriate to be introduced with the categories of DGs. Depending on the type and size, Table 4 depicts the existing categories of DGs. The four broad categories of DGs on the basis of RLP and RP delivered/absorbed to the systems are as follows (Sheng et al., 2015; Kim et al., 2008; Akram et al., 2015; Gandomkar et al., 2005; Soroudi and Ehsan, 2011; Ela et al., 2010; Wei et al., 2014; Sharma et al., 2003; Chris et al., 2015; Miranda et al., 1994; Akorede et al., 2011; Sebastian et al., 2015; Mohammadi et al., 2012; Hadi and Majid, 2012; Kim et al., 2002; Akorede et al., 2011; Vinothkumar and Selvan, 2011; Singh et al., 2009):

- (i) *DG-1 (termed as T_1):* This type of DG is capable of delivering only the RLP such as photovoltaic, micro turbines, fuel cells, bio-gas, which are integrated to the main grid with the help of converters/inverters. However, according to current situation and grid codes, the photovoltaic can be (and in sometimes is) require to provide the RP as well so that only the RLP is supplied at unity operating power factor (PF).
- (ii) *DG-2 (termed as T_2):* This type of DG is capable of delivering both the RLP and the RP. DG units based on diesel engines as diesel generators and synchronous machines (cogeneration, gas turbine etc.) come under this type of DG. For it, both the RLP and the RP are supplied at different operating PFs (e.g.0.80–0.99 leading).
- (iii) *DG-3 (termed as T_3):* This type of DG is capable of delivering only the RP. Synchronous compensators, capacitor bank, inductor bank, on line tap changing (OLTC) transformers, flexible alternating current transmission system (FACTS) controllers and gas turbines are examples of this type of DG and operate at zero PF. So, only the RP is supplied at zero operating PF for this type of DG.
- (iv) *DG-4 (termed as T_4):* This type of DG is capable of delivering the RLP but consumes the RP. Mainly, induction generators which are used in wind farms come under this category. However, doubly fed induction generators (DFIG) may consume or produce RP i.e. operates similar to synchronous generators. Here, only the RLP is supplied and the RP is drawn from the system at different operating PFs (e.g.0.80–0.99 lagging).

The mathematical formulation of DG and FACTS controller like SVC planning problem is proposed on the basis of two objective functions as follows (Sheng et al., 2015; Kim et al., 2008; Akram et al., 2015; Gandomkar et al., 2005; Soroudi and Ehsan, 2011; Ela et al., 2010; Wei et al., 2014; Sharma et al., 2003; Chris et al., 2015; Miranda et al., 1994; Akorede et al., 2011; Sebastian et al., 2015; Mohammadi et al., 2012; Hadi and Majid, 2012; Kim et al., 2002; Akorede et al., 2011; Vinothkumar and Selvan, 2011; Singh et al., 2009):

(i) *Minimization of total real power loss*: This objective function is the minimization of the total real power loss (P_{Loss}) of the system. The P_{Loss} in the system is represented by (7).

$$P_{Loss} = \sum_{x,y \in N_L} \frac{P_{xy_bus}^2 + Q_{xy_bus}^2}{|V_{x_bus}|^2} r_{xy_bus} \quad (7)$$

The P_{Loss} is function of all system bus voltage (V_{x_bus}), line resistances (r_{xy_bus}), α_{RLP} and β_{RP} . The total losses, mainly, depend on voltage profile.

(ii) *Minimization of total MVA intake at main substation*: The objective function is apparent power intake (S_{intake}) at main substation. The P_{intake} is the sum of P_{Demand} and P_{Loss} and represented by equ.

$$\begin{aligned} P_{intake} &= P_1(V, P_0, Q_0, \alpha_{RLP}, \beta_{RP}) = P_{Demand} + P_{Loss} \\ &= \sum_x^{N_B} P_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{\alpha_{RLP}} + P_{Loss} \end{aligned} \quad (8)$$

Similarly, the Q_{intake} is the sum of Q_{Demand} and Q_{Loss} and represented by (9).

$$\begin{aligned} Q_{intake} &= Q_1(V, P_0, Q_0, \alpha_{RLP}, \beta_{RP}) = Q_{Demand} + Q_{Loss} \\ &= \sum_x^{N_B} Q_{0x_bus} \left(\frac{|V_{x_bus}|}{|V_{0x_bus}|} \right)^{\beta_{RP}} + Q_{Loss} \end{aligned} \quad (9)$$

Apparent power intake at main substation is expressed in Eq. (10)

$$S_{intake} = [(P_{intake}^2) + (Q_{intake}^2)]^{1/2} \quad (10)$$

where P_{intake} = RLP intake at main substation without DG and FACTS controller like SVC; Q_{intake} = RP intake at main substation without DG and FACTS controller like SVC.

And apparent power requirement for distribution system with DG and FACTS controller like SVC is expressed by Eq. (11)

$$S_{System} = [(P_{intake} + P_{DG} + P_{FACTS})^2 + (Q_{intake} \pm Q_{DG} \pm Q_{FACTS})^2]^{1/2} \quad (11)$$

where P_{DG} & P_{FACTS} = RLP support by DG and FACTS controllers like SVC; and Q_{DG} & Q_{FACTS} = RP support/absorb by DG and FACTS controllers like SVC

It is observed that for a distribution system, Eqs. (12) and (13) hold.

$$\sum_{x=1}^{N_B} P_0(|V_{x_bus}|)^{\alpha_{RLP}} > P_{Loss} \quad (12)$$

$$\sum_{x=1}^{N_B} Q_0(|V_{x_bus}|)^{\beta_{RP}} > Q_{Loss} \quad (13)$$

Thus, the values of P_{intake} and Q_{intake} are decided, mainly, by the load exponents i.e. α_{RLP} and β_{RP} . The above objectives are subject to the following set of power flow, line limit constraint, voltage limit and voltage step limit. The RLP and RP flow are defined as in Eqs. (14)–(20).

$$\begin{aligned} P_{x_bus} &= \sum_{y=1}^{N_B} |V_{x_bus}| |V_{y_bus}| [G_{xy_bus} \cos(\delta_{x_bus} - \delta_{y_bus}) \\ &\quad + B_{xy_bus} \sin(\delta_{x_bus} - \delta_{y_bus})] \\ &\text{for } x_bus = 1 \text{ to } N_B \end{aligned} \quad (14)$$

$$\begin{aligned} Q_{x_bus} &= \sum_{y=1}^{N_B} |V_{x_bus}| |V_{y_bus}| [G_{xy_bus} \sin(\delta_{x_bus} - \delta_{y_bus}) \\ &\quad - B_{xy_bus} \cos(\delta_{x_bus} - \delta_{y_bus})] \\ &\text{for } x_bus = 1 \text{ to } N_B \end{aligned} \quad (15)$$

$$\begin{aligned} P_{x,y_bus} &= |V_{x_bus}|^2 G_{xy_bus} - |V_{x_bus}| |V_{y_bus}| \\ &\quad \times [G_{xy_bus} \cos \theta_{xy_bus} - B_{xy_bus} \sin \theta_{xy_bus}] \\ &\text{for } x, y_bus \in N_L \end{aligned} \quad (16)$$

$$\begin{aligned} Q_{x,y_bus} &= |V_{x_bus}|^2 B_{xy_bus} - |V_{x_bus}| |V_{y_bus}| \\ &\quad \times [G_{xy_bus} \sin \theta_{xy_bus} + B_{xy_bus} \cos \theta_{xy_bus}] \\ &\text{for } x, y_bus \in N_L \end{aligned} \quad (17)$$

$$V_{min} \leq |V_{x_bus}| \leq V_{max}, \quad \text{for } x_bus = 1 \text{ to } N_B \quad (18)$$

$$S_{xy_bus} \leq C_{xy_bus}^{max}, \quad \text{for } x, y_bus \in N_L \quad (19)$$

$$V_{step\ x_bus} \leq V_{step}^{max}, \quad \text{for } x_bus = 1 \text{ to } N_B \quad (20)$$

(b) Static Var Compensator (SVC): According to IEEE-CIGRE co-definition (Aziz et al., 2013; Claudio and Faur, 1999), a static var compensator is a static var generator whose output is varied so as to maintain or control specific parameters (e.g. voltage or RP of bus) of the electric power system.

SVC is a first generation FACTS controller that is already in operation at various places in the world. In its simplest form it uses a thyristor controlled reactor (TCR) in conjunction with a fixed capacitor (FC) or thyristor switched capacitor (TSC). A pair of opposite poled thyristors is connected in series with a fixed inductor to form a TCR module while the thyristors are connected in series with a capacitor to form a TSC module. An SVC can control the voltage magnitude at the required bus thereby improving the voltage profile of the system. The primary task of an SVC is to maintain the voltage of a particular bus by means of reactive power compensation (obtained by varying the firing angle of the thyristors). It can also provide increased damping to power oscillations and enhance power flow over a line by using auxiliary signals such as line RLP, line RP, line current, and computed internal frequency.

Static VAR Compensator (SVC) is a shunt connected FACTS controller whose main functionality is to regulate the voltage at a given bus by controlling its equivalent reactance. Basically it consists of a fixed capacitor (FC) and a thyristor controlled reactor (TCR). Generally they are two configurations of the SVC i.e. shown in Fig. 2(a) & (b).

(i) *SVC total susceptance model*: A changing susceptance B_{svc} represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC as shown in Fig. 2(a).

(ii) *SVC firing angle model*: The equivalent reactance X_{SVC} , which is function of a changing firing angle α , is made up of the parallel combination of a thyristor controlled reactor (TCR) equivalent admittance and a fixed capacitive reactance as shown in Fig. 2(b). This model provides information on the SVC firing angle required to achieve a given level of compensation.

Fig. 3 shows the steady-state and dynamic voltage-current characteristics of the SVC. In the active control range, current/susceptance and RP is varied to regulate voltage according to

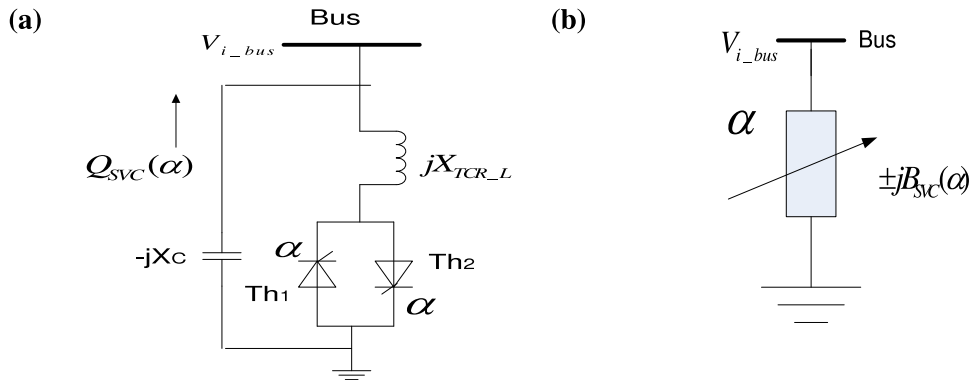


Fig. 2. SVC (a) firing angle model and (b) total susceptance model.

a slope (droop) characteristic. The slope value depends on the desired voltage regulation, the desired sharing of RP production between various sources, and other needs of the system. The slope is typically 1%–5%. At the capacitive limit, the SVC becomes a shunt capacitor. At the inductive limit, the SVC becomes a shunt reactor (the current or RP may also be limited).

SVC firing angle model is implemented in this paper. Thus, the model can be developed with respect to a sinusoidal voltage, differential and algebraic equations can be written as $S_{SVC_FACTS} = -jB_{SVC_FACTS}V_{k_bus}$. The fundamental frequency TCR equivalent reactance X_{SVC_TCR}

$$X_{SVC_TCR} = \frac{\pi X_L}{\eta - \sin \eta}$$

where $\eta = 2(\pi - \alpha)$, $X_L = \omega L$ and in terms of firing angle in Eq. (21).

$$X_{SVC_TCR} = \frac{\pi X_L}{2(\pi - \alpha) + \sin(2\alpha)} \tag{21}$$

where η and α are conduction and firing angles respectively.

At $\alpha = 90^\circ$, TCR conducts fully and the equivalent reactance X_{SVC_TCR} becomes X_L , while at $\alpha = 180^\circ$, TCR is blocked and its equivalent reactance becomes infinite. The SVC effective reactance X_{SVC_equ} is determined by the parallel combination of X_{Cap} and X_{SVC_TCR} is given in Eqs. (22)–(23).

$$X_{SVC_equ}(\alpha) = \frac{\pi X_{Cap}X_L}{X_{Cap}[2(\pi - \alpha) + \sin(2\alpha)] - \pi X_L} \tag{22}$$

where $X_{Cap} = \frac{1}{\omega C}$

$$Q_{SVC} = Q_{FACTS} = -V_{k_bus}^2 \left\{ \frac{X_{Cap}[2(\pi - \alpha) + \sin(2\alpha)]}{\pi X_{Cap}X_L} \right\} \tag{23}$$

The SVC equivalent reactance is given above equation. It is shown in Fig. 4 that the SVC equivalent susceptance ($B_{SVC} = -1/X_{SVC}$) profile, as function of firing angle, does not present discontinuities, i.e., B_{SVC} varies in a continuous, smooth fashion in both operative regions. Hence, linearization of the SVC power flow equations, based on B_{SVC} with respect to firing angle, will exhibit a better numerical behavior than the linearized model based on X_{SVC} .

The initialization of the SVC variables based on the initial values of ac variables and the characteristic of the equivalent susceptance is shown in Fig. 4, thus the impedance is initialized at the resonance point $X_{SVC_TCR} = X_{Cap}$, i.e. $Q_{SVC} = 0$, corresponding to firing angle of SVC is near about 115° , for chosen parameters of L and C i.e. X_L is 0.1134Ω : and X_{Cap} is 0.2267Ω (Aziz et al., 2013; Claudio and Faur, 1999).

The mode of operation of SVC are as follows:

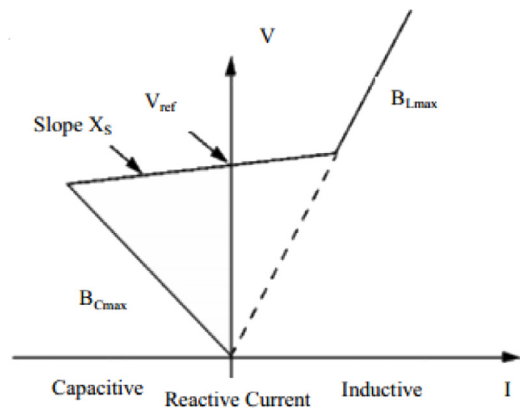


Fig. 3. The V-I characteristics of SVC.

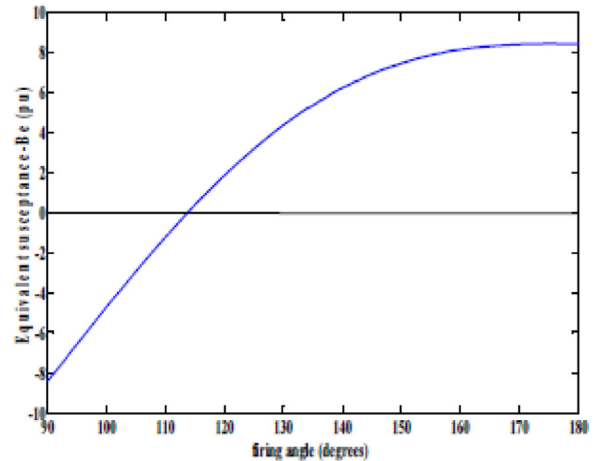


Fig. 4. SVC equivalent susceptance profile.

- (i) *SVC behaves as load mode*: SVC behaves as load mode means that RP absorb from the system bus when firing angle of SVC is 115.44° ;
- (ii) *SVC behaves as generator mode*: SVC behaves as generator mode means that RP feed to the system when firing angle of SVC is 112.25° ;
- (iii) *SVC behaves as resonance mode*: SVC behaves as resonance mode means that RP neither deliver nor absorb from the system bus when firing angle of SVC is 113.82° . The values of different firing angles of SVC and its corresponding RP delivered/absorbed are given in Table 5.

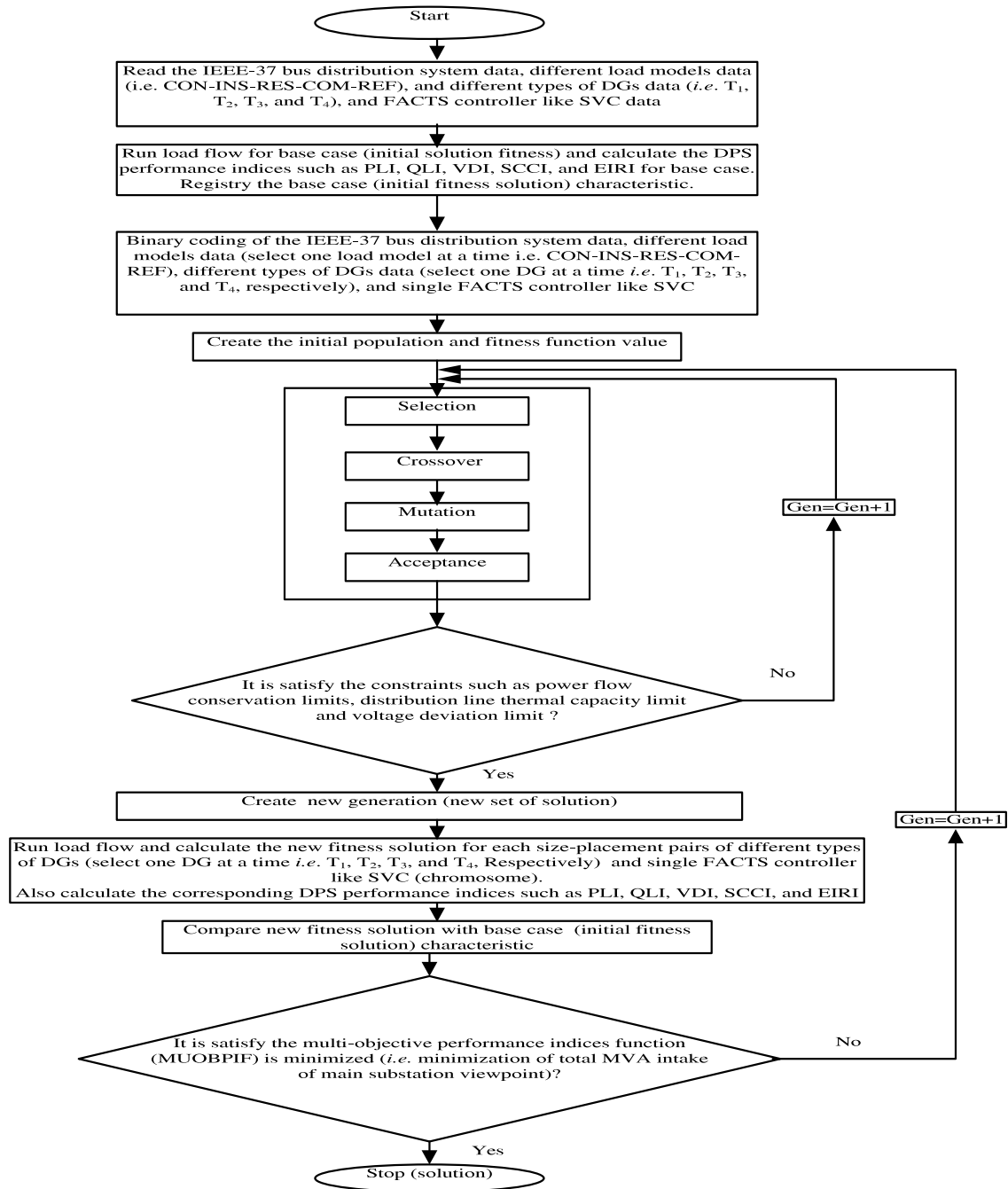


Fig. 5. Flowchart for proposed methodology such as GA for impact assessment of optimally placed different types of DGs with DLMs in DPSs from minimum total MVA intake viewpoint of main substation.

Table 5
SVC data (Aziz et al., 2013; Claudio and Faur, 1999).

SVC _{alpha} (in degree)	Q _{SVC} (in p.u.)	Mode of operation of SVC
115.44	−0.250	as SVC load
117.09	−0.500	as SVC load
113.82	0.000	SVC in resonance (Floating stage)
112.25	+ 0.250	as SVC generator
110.71	+ 0.500	as SVC generator

2.2.2. DPS performance indices

The different DPS performance indices for impact assessment of DG and FACTS controller like SVC on DPSs are defined as follows (Sheng et al., 2015; Kim et al., 2008; Akram et al., 2015;

Gandomkar et al., 2005; Soroudi and Ehsan, 2011; Ela et al., 2010; Wei et al., 2014; Sharma et al., 2003; Chris et al., 2015; Miranda et al., 1994; Akorede et al., 2011; Sebastian et al., 2015; Mohammadi et al., 2012; Hadi and Majid, 2012; Kim et al., 2002; Akorede et al., 2011; Vinothkumar and Selvan, 2011; Singh et al., 2009).

(i) RLP loss index (PLI): The RLP loss index is defined by Eq. (24).

$$PLI = \frac{|P_{Loss_WDG_SVC_FACTS}|}{|P_{Loss_WODG_SVC_FACTS}|} \times 100\% \tag{24}$$

where $P_{Loss_WDG_SVC_FACTS}$ is the RLP loss with DG and FACTS controller like SVC and $P_{Loss_WODG_SVC_FACTS}$ is the RLP loss without DG and FACTS controller like SVC. The lower value of this index indicates a better benefit in terms of RLP loss reduction has

Table 6

Important pollutants emission of main substation (Chiradeja and Ramakumar, 2004).

Pollutants emission of GHG level	CO ₂ in kg/MWh	SO ₂ in kg/MWh	NO _x in kg/MWh	Particulate matters
Main substations	970	0.6396	0.3129	0.1270

Table 7

Important pollutants emission of different types of DGs (Chiradeja and Ramakumar, 2004).

Pollutant emission of GHG level	CO ₂ in kg/MWh	SO ₂ in kg/MWh	NO _x in kg/MWh	Particulate matters	
Different types of DGs	T ₁	490	0.0004536	0.004536	0.000000
	T ₂	825	0.181400	5.21630	0.84820
	T ₃	75	0.0001568	0.001568	0.00000
	T ₄	202	0.0027220	0.004536	0.00000

Table 8

Values of weight factors of pollutants emission indices on merit/priority basis.

Pollutants	Weight factors
Carbon dioxide (CO ₂)	$El_{CO_2} = 0.4$
Sulfur dioxide (SO ₂)	$El_{SO_2} = 0.3$
Nitrogen oxide (NO _x)	$El_{NO_x} = 0.2$
Particulate matters	$El_{particulate} = 0.1$

Table 9

Values of weight factors of DPS performance indices on merit/priority basis.

Weight factors for DPS performance indices	Values as per priority basis
μ_1	0.40
μ_2	0.30
μ_3	0.10
μ_4	0.10
μ_5	0.10

occurred due to DG and FACTS controller like SVC placement and size.

(ii) *RP loss index (QLI)* The RP loss index is defined as in Eq. (25).

$$QLI = \frac{|Q_{Loss_WDG_SVC_FACTS}|}{|Q_{Loss_WODG_SVC_FACTS}|} \times 100\% \quad (25)$$

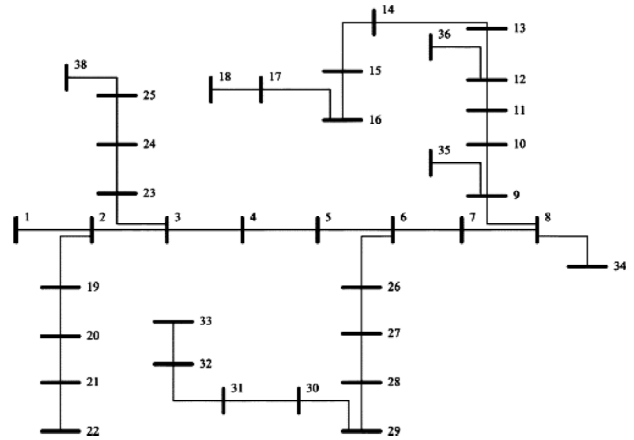
where $Q_{Loss_WDG_SVC_FACTS}$ is the RP loss with DG and FACTS controller like SVC and $Q_{Loss_WODG_SVC_FACTS}$ is the RP loss without DG and FACTS controller like SVC. The lower value of this index indicates a better benefit in terms of RP loss reduction has occurred due to DG and FACTS controller like SVC placement and size.

(iii) *Voltage deviation index (VDI)*: One of the advantage of proper placement and size of different types of DGs and single FACTS controller like SVC is the improvement in voltage profile. This index penalizes the size–location pair which gives higher voltage deviations from the nominal ($V_1 = 1.03$ p.u.). In this way, closer the index to zero better is the network performance. It is related to the maximum voltage drop between each node and root node. The VDI can be defined as in Eq. (26).

$$VDI = \max \left(\frac{|\bar{V}_1| - |\bar{V}_{x_bus_WDG_SVC_FACTS}|}{|\bar{V}_1|} \right) \times 100\% \quad \text{for } x_bus = 2 \text{ to } N_B \quad (26)$$

where \bar{V}_1 is the slack bus voltage and $\bar{V}_{i_bus_WDG_SVC_FACTS}$ is the voltage at i th bus with DG and FACTS controller like SVC. The lower value of this index indicates better performance of DPSs. Normally, the voltage limits ($V_{min} \leq V_{x_bus} \leq V_{max}$) at a particular bus is taken as technical constraint, and thus the value of VDI is normally small and within the permissible limits.

(iv) *Short circuit current or MVA line capacity index (SCCI)*: The power flow may diminish in some section of the network and release more capacity with the power supplied nearer to the load.

**Fig. 6.** Single-line diagram of IEEE 37-bus (38-node) distribution test system [55–61].

This index is defined by Eq. (27).

$$SCCI = \max \left(\frac{|\bar{S}_{xy_bus_WDG_SVC_FACTS}|}{|\bar{C}_{S_{xy_bus}}|} \right) \times 100 \quad \text{for } xy_bus \text{ set} = 1 \text{ to } N_L \quad (27)$$

where $\bar{C}_{S_{xy_bus}}$ is the MVA line capacity without DG and FACTS controller like SVC, $\bar{S}_{xy_bus_WDG_SVC_FACTS}$ is the MVA line capacity with DG and FACTS controller like SVC. As a consequence of supplying power near to loads, MVA flows may diminish in some sections of the network, thus releasing more capacity, but in other sections they may also increase to levels beyond distribution line limits (if line limits are not taken as constraints). This index provides important information about the level of power flows/currents through the network regarding maximum capacity of the distribution lines.

This gives the information about need of system line upgrades. Values higher than unity (calculated MVA flow values higher than the MVA capacity) of the index give the amount of capacity violation in term of line flows, whereas the lower values indicate the capacity available.

The benefit of placing of different types of DGs and FACTS controller like SVC in a system in context of line capacity released is measured by finding the difference in SCCI between system with and without DG and FACTS controller like SVC. The avoidance of flow near to the flow limit is an important criterion as it indicates that how earlier the system needs to be upgraded and thus adding to the cost. The use of SCCI index may not be applicable in the context available transmission capacity improvement in transmission systems. Normally, the limits ($S_{(x,y_bus)} \leq S_{(x,y_bus)max}$) at a particular line is taken as a strict constraint, and thus the value of SCCI is always positive. Lower value of this index indicates that

more capacity is available. Index values more than 100% indicate that lines are overloaded.

(V) *Environmental impact reduction index (EIRI)*: Another potential benefit of DG and FACTS controller like SVC is the production of energy with minimal GHG emissions and other pollutants as compared to conventional technologies. Concerns about GHG effect are growing rapidly in the public's view. GHG effect is a result of rising in levels of carbon dioxide and other GHG emissions. It is believed that GHG effect will lead to global warming and world-wide climate change. Introduction of DG and FACTS controller like SVC will result in a reduction of capacity needs of conventional plants due to two reasons viz. (a) the RLP generated by DG and FACTS controller like SVC units will directly reduce the output requirements and (b) the resulting line loss reduction will further decrease the output needs from the conventional plants. The basic idea behind the EIRI (defined latter in (32)) is to compare the emission of a particular pollutant with and without the employment of DG and FACTS controller like SVC. This is defined by (28) (Chiradeja and Ramakumar, 2004).

$$EIR_Index_{i_pollutant}^k = \frac{|PE_{iw_WDG_SVC_FACTS}|}{|PE_{iw_WODG_SVC_FACTS}|} \times 100\% \quad (28)$$

for the i th pollutant (CO_2 , SO_2 , NO_x , etc.); where $PE_{iw_WDG_SVC_FACTS}$ and $PE_{iw_WODG_SVC_FACTS}$ are the amounts of emissions with and without DG and FACTS controller like SVC, respectively, for the p th pollutant and these are defined as in Eqs. (29) and (30).

$$PE_{iw_WDG_SVC_FACTS} = \sum_{m=1}^{N_G} (EG)_{Bm} (AE)_{im} + \sum_{n=1}^{N_{DG}} (EDG)_n (AE)_{in} + \sum_{l=1}^{N_{FACTS}} (ESVC_FACTS)_l (AE)_{il} \quad (29)$$

$$PE_{iw_WODG_SVC_FACTS} = \sum_{m=1}^{N_G} (EG)_m (AE)_{im} \quad (30)$$

where $(EG)_{Bm}$, and $(EG)_m$ are the amounts of electrical energy generated by the m th conventional power plant with and without the employment of DG and FACTS controller like SVC, respectively (MWh); $(AE)_{im}$ is the amount of emission of the i th pollutant for the m th conventional plant per MWh of energy generated and N_G is the total number of conventional generators in the system; $(AE)_{in}$ is the amount of emission of the i th pollutant for the n th DG power plant per MWh of energy generated; $(AE)_{il}$ is the amount of emission of the i th pollutant for the l th FACTS controller like SVC power plant per MWh of energy generated; $(EDG)_n$ is the amount of energy generated by the n th DG plant (MWh) and N_{DG} is the total number of DG plants in the system; $(ESVC_FACTS)_l$ is the amount of energy generated by the n th FACTS controller like SVC plant (MWh) and N_{FACTS} is the total number of FACTS controllers plants in the system. Once again, the loads supplied at different buses are assumed to be the same in both cases i.e. with and without DG. In reality, power plants emit many pollutants into the atmosphere. Thus, it is useful to define a composite index to include all the major associated pollutants. This index (termed as EIRI) can be formulated as in Eqs. (31)–(33).

$$EIRI = 1 - \sum_{i=1}^{N_i} (EI)_i * (EIR_Index_{i_pollutant}^k) \quad (31)$$

with

$$0 \leq (EI)_i \leq 1 \quad (32)$$

and

$$\sum_{i=1}^{N_i} (EI)_i = 1 \quad (33)$$

where $(EI)_i$ is the weighting factor for the i th pollutant and N_i is total number of pollutants of interest. The details of important pollutants emission levels of conventional generators and DGs and FACTS controller like SVC such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxide (NO_x) and particulate matters are given in Tables 6 and 7, respectively.

Table 8 shows the value for the weights used in present work, considering normal operation analysis and is similar to Chiradeja and Ramakumar (2004). However, these values may vary according to an engineer's concerns. In this analysis carbon dioxide (CO_2) emission received a first significant weight (0.40). The sulfur dioxide (SO_2) emission received a second significant weight (0.3). The nitrogen oxide (NO_x) emission received a third significant weight (0.2). The particulate matters emission received a fourth significant weight (0.1).

3. GA implementation

(a) *A brief overview of GA*: GA (Al Abri et al., 2013; Sheng et al., 2015; Kim et al., 2008; Akram et al., 2015; Gandomkar et al., 2005; Soroudi and Ehsan, 2011; Ela et al., 2010; Wei et al., 2014; Sharma et al., 2003; Chris et al., 2015; Miranda et al., 1994; Akorede et al., 2011; Sebastian et al., 2015; Mohammadi et al., 2012; Hadi and Majid, 2012; Kim et al., 2002; Akorede et al., 2011; Vinothkumar and Selvan, 2011; Singh et al., 2009) is a search technique used in computing to find true or approximate solutions to optimization and search problems. GAs is adaptive heuristic search algorithm premised on the evolutionary ideas of natural selection and genetic. The basic concept of GAs is designed to simulate processes in natural system necessary for evolution, specifically those that follow the principles first laid down by Charles Darwin of survival of the fittest.

Reasons for using GA for different types of DGs and FACTS controller like SVC planning are as follows:

- (i) It is better than conventional artificial intelligent techniques. It is more robust.
- (ii) Unlike older AI systems, the GAs do not beak easily even if the inputs changed slightly, or in the presence of reasonable noise.
- (iii) While performing search in large state-space, or multi-modal state space, or n-dimensional surface, GAs offer significant benefits over other typical search optimization techniques like linear programming, heuristic, depth first, breath-first.

The applications of GAs in machine learning, mechanical engineering, electrical engineering, civil engineering, data mining, chemical engineering, and image processing, are dealt to make the authors understand where the concept can be applied.

(b) *Basic GA operators*: Usually, GA uses three simple operators called as selection, recombination or crossover, and mutation as discussed in Singh et al. (2009). Taken together, selection, crossover and mutation are called reproduction which is analogous to biological crossover and mutations as discussed in [66]. These operations are discussed in detail as follows:

- (i) *Selection*: Reproduction involves selection of chromosomes for the next generation. In the most general case, the fitness of an individual determines the probability of its survival for the next generation. There are different selection procedures in GA depending on how the fitness values are used.

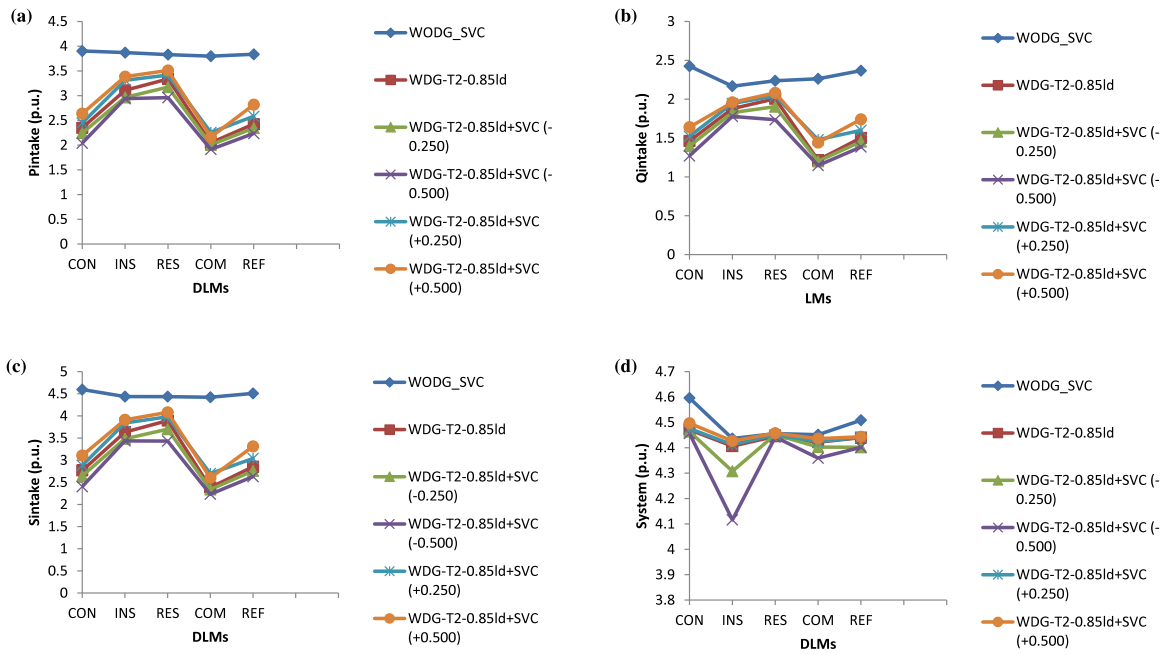


Fig. 7. Pertaining to DG (i.e. T_2 operating at 0.85 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF) in DPSs, profiles of (a) P_{intake} , (b) Q_{intake} , (c) S_{intake} , and (d) S_{system} . *'ld' means leading operating PFs of DGs; $T_2 = T_2$ type of DG.

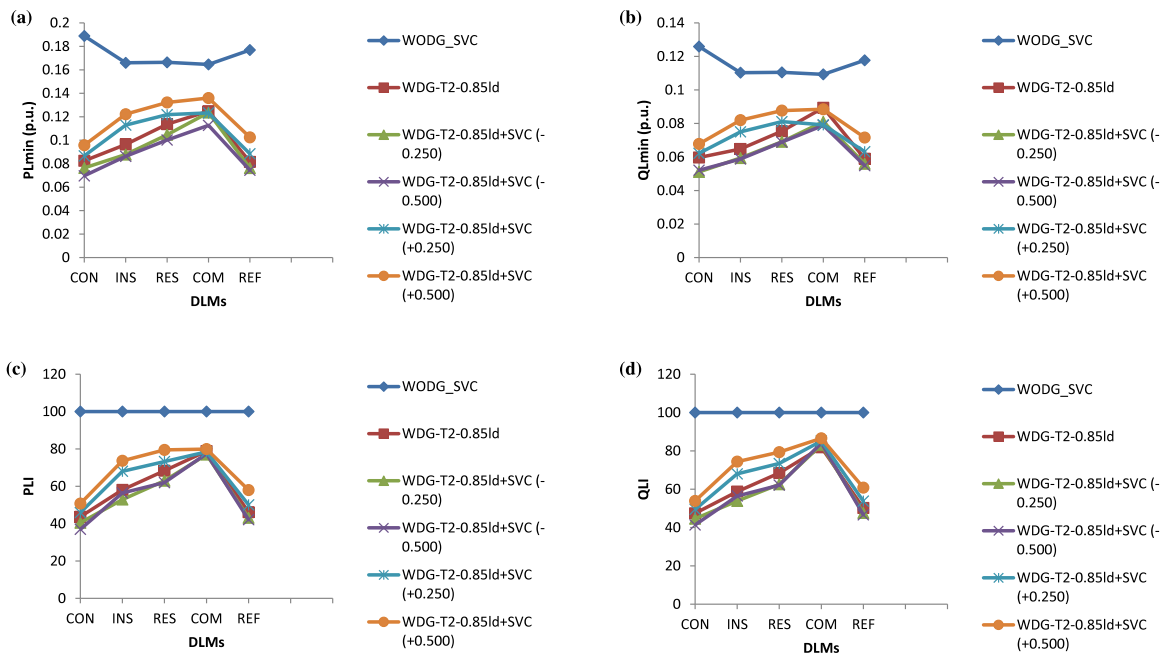


Fig. 8. Pertaining to DG (i.e. T_2 operating at 0.85 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{Lmin} , (b) Q_{Lmin} , (c) PLI , and (d) QLI . *'ld' means leading operating PFs of DGs; $T_2 = T_2$ type of DG.

After initialization the value of objective function is calculated. Corresponding to the value of objective function the next operation selection is done. The following selection process such as deterministic selection, roulette wheel selection, stochastic selection without replacement, remainder stochastic sampling with replacement, and stochastic sampling with replacement are used in the system. Out of these selections process the roulette selection processes is considered in this paper since it gives fitness values for each individual values and that is the most important advantage, and with that the optimal evaluation in distribution system is done.

(ii) *Crossover*: The crossover operator is the most important operator of GA. In crossover, generally two chromosomes, called parents, are combined together to form new chromosomes, called offspring. The parents are selected from existing chromosomes in the population with reference toward fitness so that offspring is expected to inherit good genes which make the parents fitter. By iteratively applying the crossover operator, genes of good chromosomes are expected to appear more frequently in the population, eventually leading to convergence to an overall good solution. Crossover probability is taken 0.95.

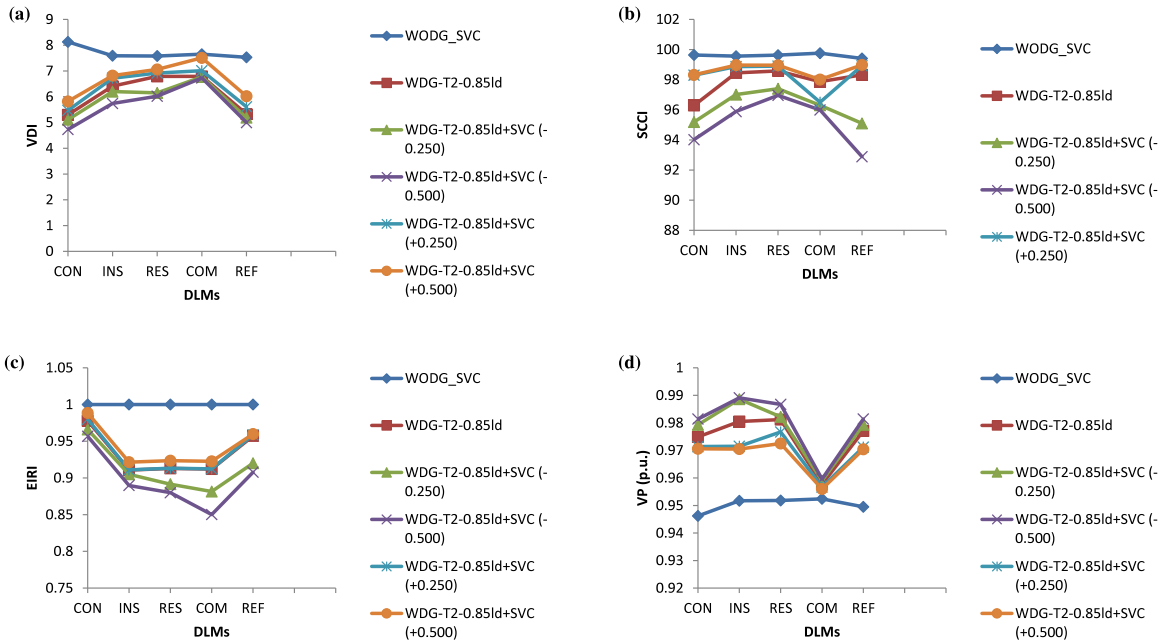


Fig. 9. Pertaining to DG (i.e. T_2 operating at 0.85 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) VDI, (b) SCCI, (c) EIRI, and (d) VP. *ld' means leading operating PFs of DGs; T2 = T_2 type of DG.

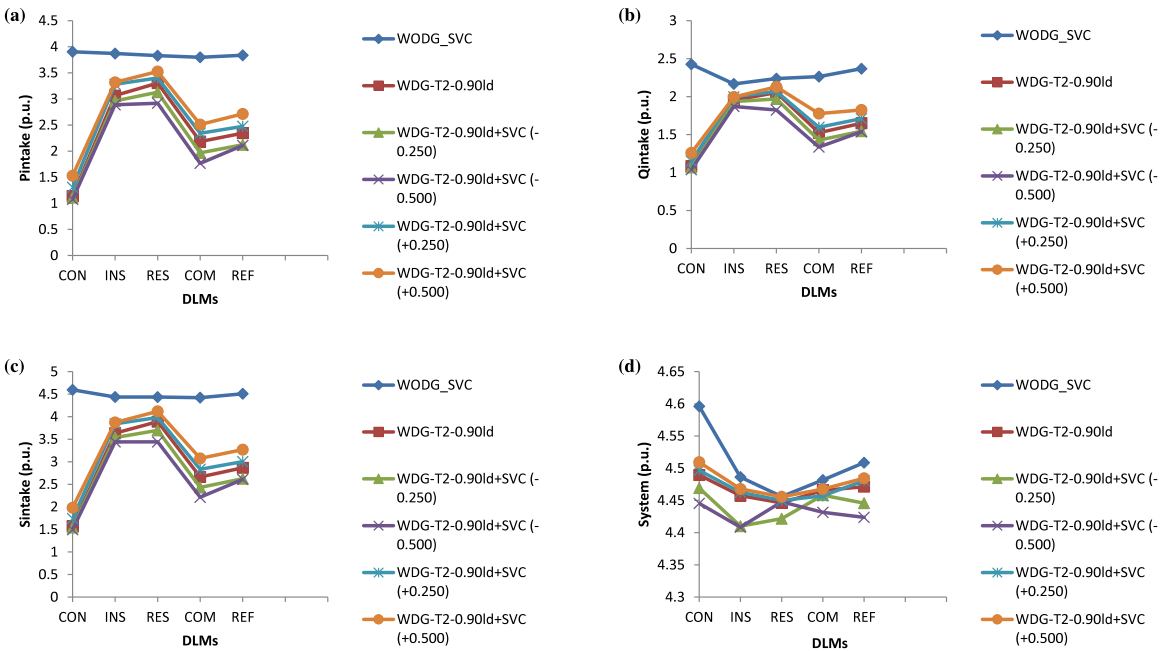


Fig. 10. Pertaining to DG (i.e. T_2 operating at 0.90 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{intake} , (b) Q_{intake} , (c) S_{intake} , and (d) S_{system} . *ld' means leading operating PFs of DGs; T2 = T_2 type of DG.

(iii) **Mutation:** The mutation operator introduces random changes into characteristics of chromosomes. Mutation is generally applied at the gene level. In typical GA implementations, the mutation rate is very small, typically less than 10%. However, the mutation plays a critical role in GA. As discussed earlier, crossover leads the population to converge by making the chromosomes in the population alike. Mutation reintroduces genetic diversity back into the population and assists the search escape from local optima. Mutation probability has taken 0.15.

(c) **GA implementation:** In this paper, a GA optimization technique developed in a previous work of [55] and [56] has been used for finding the best solutions of the MUOPIF optimization algorithm. The first important aspect of correct GA implementation is the examination of potential solution. If the network structure is fixed, all the branches between buses are known, and the evaluation of the objective functions depend only on size and placement of different types of DGs and FACTS controller like SVC. For this reason each solution is examined for proper placement and corresponding size of different types of DGs unit. The implemented GA starts by randomly generating an initial population of the possible solutions. For each solution a size of DG

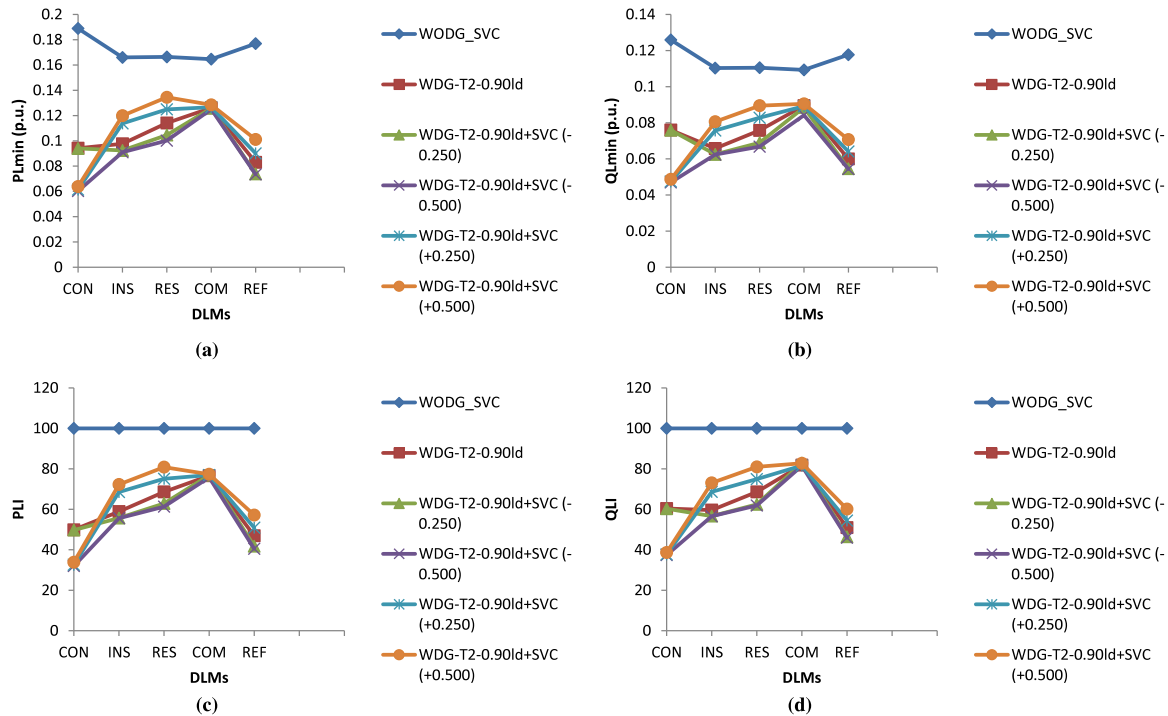


Fig. 11. Pertaining to DG (i.e. T_2 operating at 0.90 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{Lmin} , (b) Q_{Lmin} , (c) PLI, and (d) QLI. *ld' means leading operating PFs of DGs; $T_2 = T_2$ type of DG.

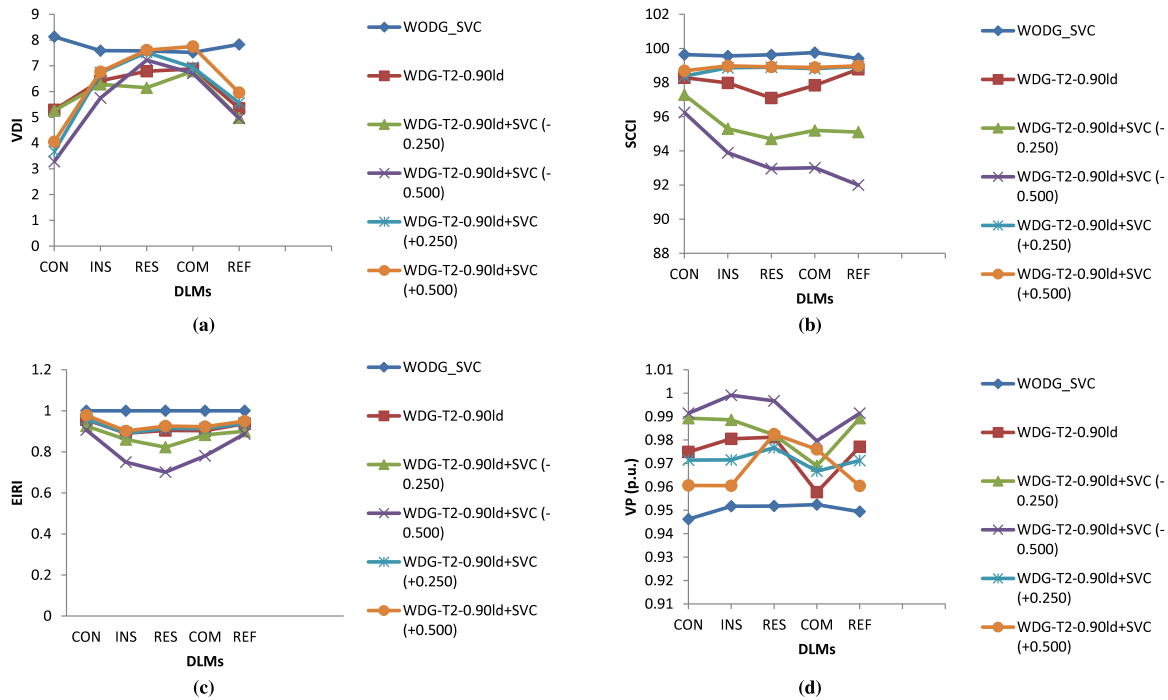


Fig. 12. Pertaining to DG (i.e. T_2 operating at 0.90 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) VDI, (b) SCCI, (c) EIRI, and (d) VP. *ld' means leading operating PFs of DGs; $T_2 = T_2$ type of DG.

and FACTS controller like SVC and a placement (bus) are generated by the planner with economical and technical justifications. A number of size–placement pairs are randomly chosen until the total power loss of the system is optimal (or near optimal) for DG and FACTS controller like SVC penetration level. At this point objective function is evaluated for verifying all technical constraints. If any one of them is violating, then such solution is rejected.

Once population cycle is initialized, the genetic operators are repeatedly applied in order to produce new solutions. By applying crossover and mutation operators new population is generated. If one of the technical constraints is violated or the DG and FACTS controller like SVC size and /or placement exceed the limit, new solution is rejected.

Finally, according to the GA theory, the new population is formed comparing old and new solutions and choosing the best

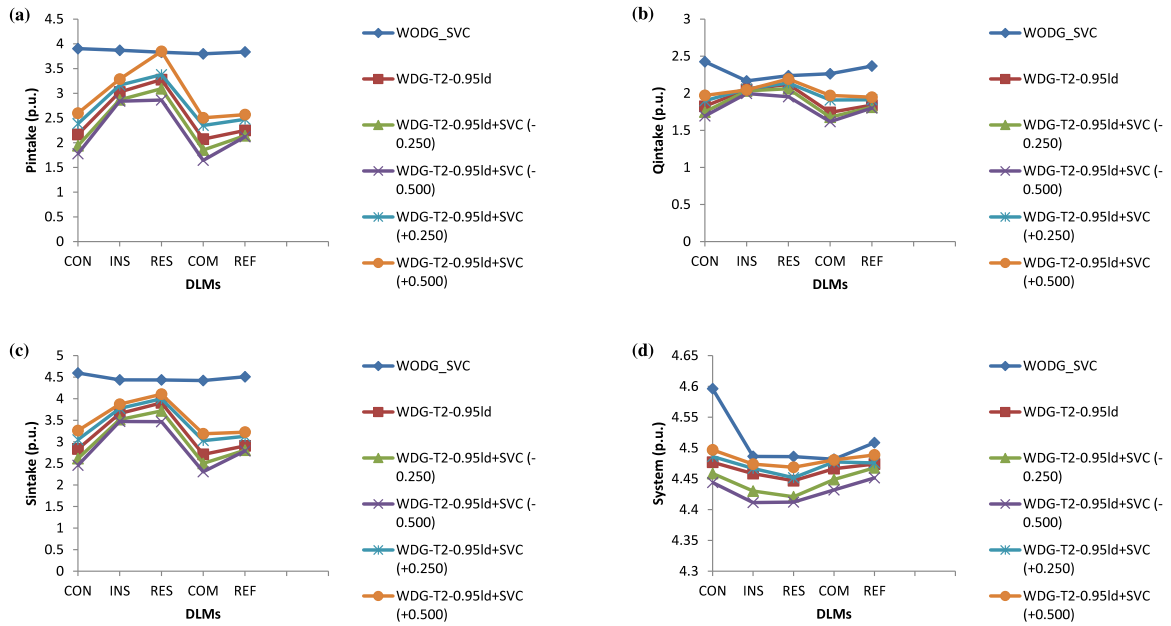


Fig. 13. Pertaining to DG (i.e. T_2 operating at 0.95 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{intake} , (b) Q_{intake} , (c) S_{intake} , and (d) S_{system} . *ld' means leading operating PFs of DGs; $T_2 = T_2$ type of DG.

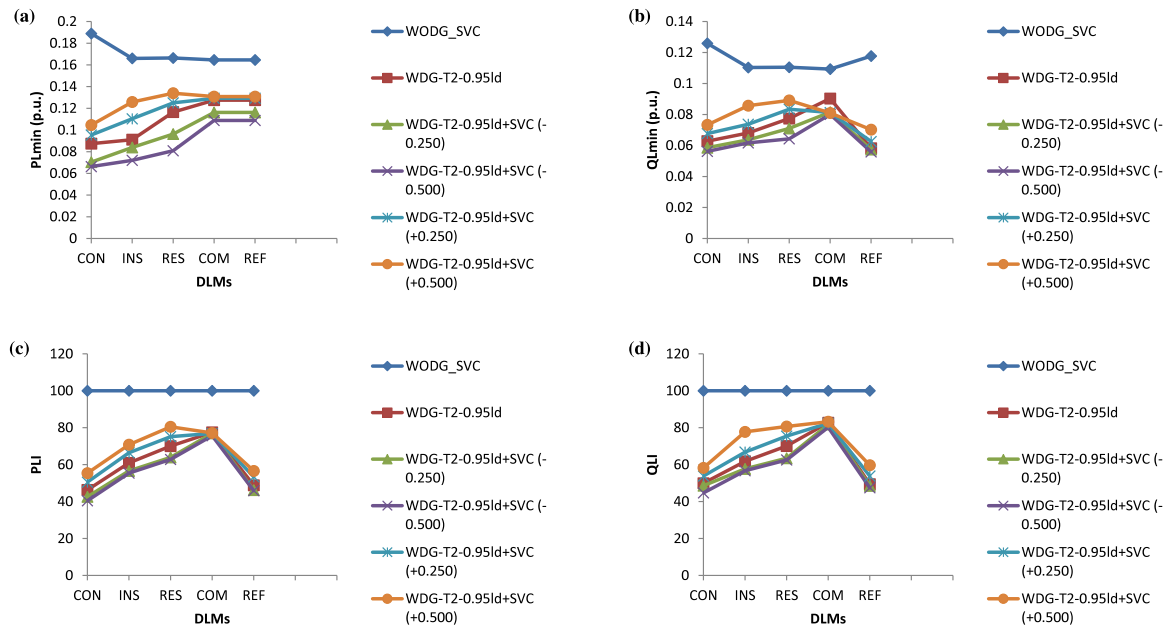


Fig. 14. Pertaining to DG (i.e. T_2 operating at 0.95 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{Lmin} , (b) Q_{Lmin} , (c) PLI, and (d) QLI. *ld' means leading operating PFs of DGs; $T_2 = T_2$, type of DG.

among them. The algorithm stops when the maximum number of generation is reached or difference between objective function value of the best and worst individuals becomes smaller than specified value.

The various steps for algorithms of GA for optimal placement of different types of DG and FACTS controller like SVC with DLMs in DPSs from minimum total MVA intake of main substation viewpoint are as follows:

1. **[Read the data]:** Read the IEEE 37-bus distribution system data, different load models data (i.e. CON–INS–RES–COM–REF), and different types of DG data (i.e. T_2 and T_4 are operating at different power factors such as 0.85, 0.90,

0.95, and 0.99 leading and lagging, respectively) and FACTS controller like SVC data.

2. **[Run load flow for base case (initial fitness solution)]:** Run load flow for base case (initial solution fitness) and calculate the PS performance indices such as PLI, QLI, VDI, SCCI, and EIRI for base case. Registry the base case (initial fitness solution) characteristic.
3. **[Binary coding]:** Binary coding of the IEEE 37-bus distribution system data, different load models data (select one load model at a time i.e. CON–INS–RES–COM–REF), and different types of DG data (select one DG at a time i.e. T_2 and T_4 are operating at different power factors such as 0.85, 0.90, 0.95, and 0.99 leading and lagging, respectively) and single FACTS controller like SVC data.

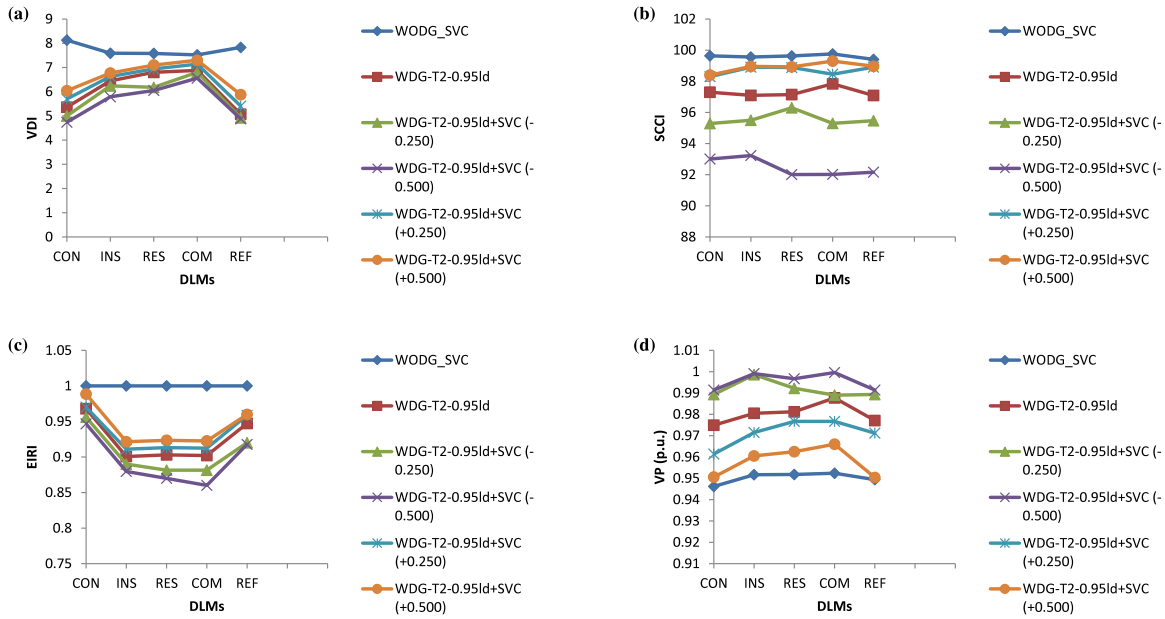


Fig. 15. Pertaining to DG (i.e. T_2 operating at 0.95 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) VDI, (b) SCCI, (c) EIRI, and (d) VP. *'ld' means leading operating PFs of DGs; $T_2 = T_2$ type of DG.

Table 10
System and load data for IEEE 37-bus distribution test system (Singh et al., 2009).

From	To	Line Impedance in p.u.			Load on to node (p.u.)				
		$R_{p.u.}$	$X_{p.u.}$	L	S_L	P_L	Q_L	L_T	
1	2	0.000574	0.000293	1	4.6	0.1	0.06	R	
2	3	0.00307	0.001564	6	4.1	0.09	0.04	I	
3	4	0.002279	0.001161	11	2.9	0.12	0.08	C	
4	5	0.002373	0.001209	12	2.9	0.06	0.03	R	
5	6	0.0051	0.004402	13	2.9	0.06	0.02	I	
6	7	0.001166	0.003853	22	1.5	0.2	0.1	C	
7	8	0.00443	0.001464	23	1.05	0.2	0.1	C	
8	9	0.006413	0.004608	25	1.05	0.06	0.02	I	
9	10	0.006501	0.004608	27	1.05	0.06	0.02	C	
10	11	0.001224	0.000405	28	1.05	0.045	0.03	C	
11	12	0.002331	0.000771	29	1.05	0.06	0.035	R	
12	13	0.009141	0.007192	31	0.5	0.06	0.035	C	
13	14	0.003372	0.004439	32	0.45	0.12	0.08	R	
14	15	0.00368	0.003275	33	0.3	0.06	0.01	C	
15	16	0.004647	0.003394	34	0.25	0.06	0.02	I	
16	17	0.008026	0.010716	35	0.25	0.06	0.02	C	
17	18	0.004558	0.003574	36	0.1	0.09	0.04	I	
2	19	0.001021	0.000974	2	0.5	0.09	0.04	R	
19	20	0.009366	0.00844	3	0.5	0.09	0.04	C	
20	21	0.00255	0.002979	4	0.21	0.09	0.04	I	
21	22	0.004414	0.005836	5	0.11	0.09	0.04	R	
3	23	0.002809	0.00192	7	1.05	0.09	0.04	C	
23	24	0.005592	0.004415	8	1.05	0.42	0.2	C	
24	25	0.005579	0.004366	9	0.5	0.42	0.2	C	
6	26	0.001264	0.000644	14	1.5	0.06	0.025	C	
26	27	0.00177	0.000901	15	1.5	0.06	0.025	I	
27	28	0.006594	0.005814	16	1.5	0.06	0.02	C	
28	29	0.005007	0.004362	17	1.5	0.12	0.07	C	
29	30	0.00316	0.00161	18	1.5	0.2	0.6	C	
30	31	0.006067	0.005996	19	0.5	0.15	0.07	R	
31	32	0.001933	0.002253	20	0.5	0.21	0.1	R	
32	33	0.002123	0.003301	21	0.1	0.06	0.04	C	
8	34	0.012453	0.012453	24	0.5	0	0		
9	35	0.012453	0.012453	26	0.5	0	0		
12	36	0.012453	0.012453	30	0.5	0	0		
18	37	0.003113	0.003113	37	0.5	0	0		
25	38	0.00313	0.003113	10	0.1	0	0		

L = Line number, S_L = Line MVA limit in p.u., P_L = Real MW load in p.u., Q_L = Reactive MVA load in p.u., L_T = Load type, R = Residential, I = Industrial, C = Commercial.

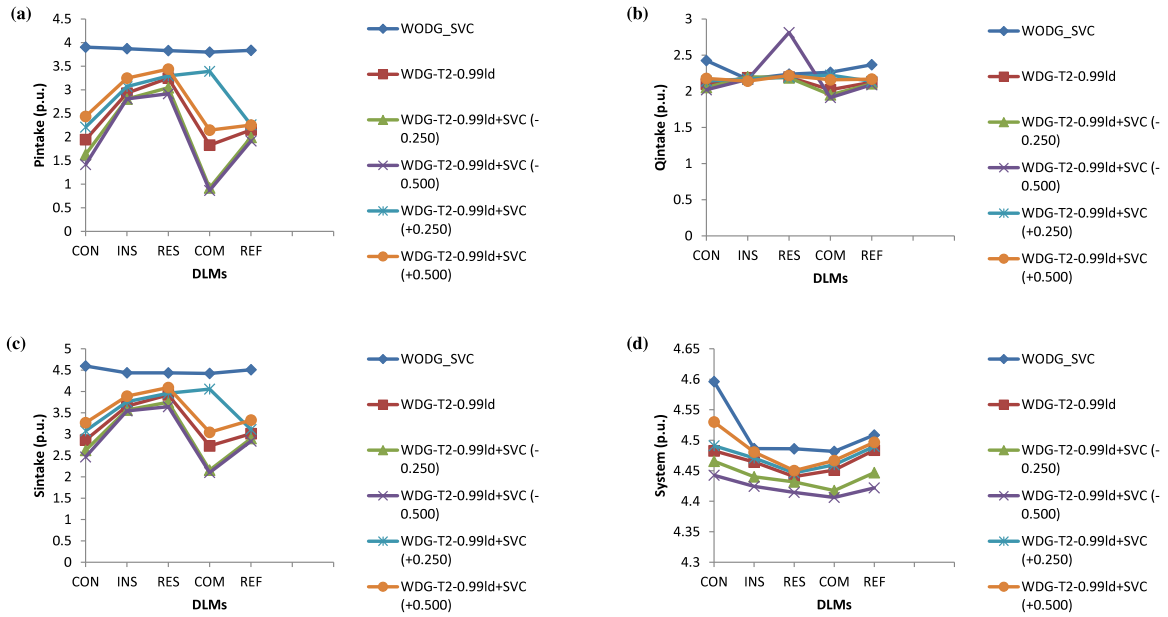


Fig. 16. Pertaining to DG (i.e. T_2 operating at 0.99 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{intake} , (b) Q_{intake} , (c) S_{intake} , and (d) S_{system} . *'ld' means leading operating PFs of DGs; $T_2 = T_2$ type of DG.

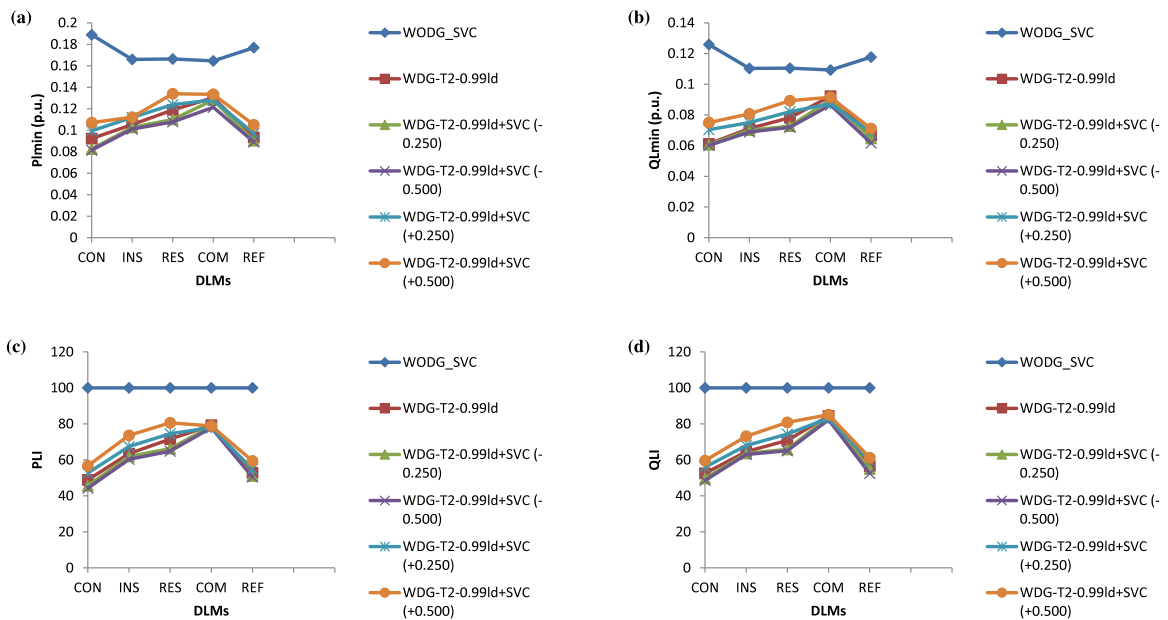


Fig. 17. Pertaining to DG (i.e. T_2 operating at 0.99 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{Lmin} , (b) Q_{Lmin} , (c) PLI , and (d) QLI . *'ld' means leading operating PFs of DGs; $T_2 = T_2$ type of DG.

4. **[Initialization]** Create the initial population and fitness function value: Generate the random population of n chromosomes (suitable solutions for the problem):randomly generate size–placement pairs of different types of DG (i.e. select one DG at a time T_2 and T_4 are operating at different power factors such as 0.85, 0.90, 0.95, and 0.99 leading and lagging, respectively) with DLMs (i.e. select one load model at a time i.e. CON–INS–RES–COM–REF) in a predefined range of size–placement of different types of DG single FACTS controller like SVC.
5. **[Fitness function value]** Evaluate the fitness function value $[f(x)]$ of each size–placement of different types of DG and single FACTS controller like SVC (chromosome) x in the population: run load flow and calculate PS performance

indices such as PLI , QLI , VDI , $SCCI$ and $EIRI$ for each size–placement pairs under uniform loading condition. Record the DPS performance indices and its corresponding size–placement pairs.

6. **[New population]** Create a new population by repeating following steps until the new population is complete:
 - (a) **[Selection]** Select two parent chromosomes from a population according to their fitness (better the fitness, bigger is the chance to be selected).
 - (b) **[Crossover]** With a crossover probability the parents crossover to form a new offspring (children). If no crossover is performed, offspring would be an exact copy of parents.

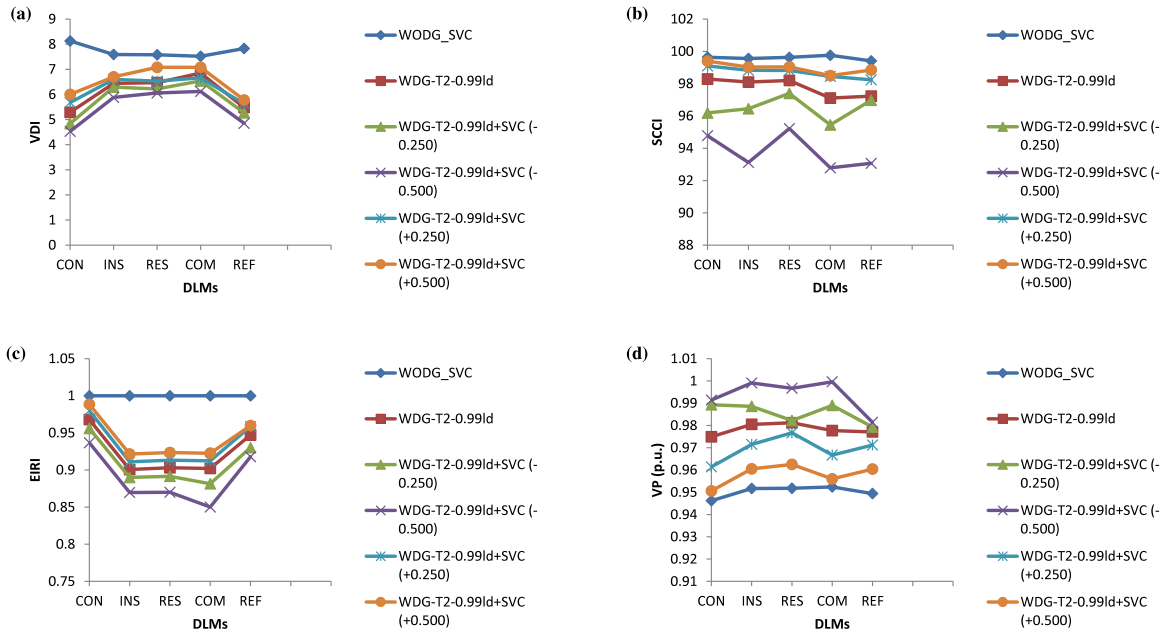


Fig. 18. Pertaining to DG (i.e. T_2 operating at 0.99 leading PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) VDI, (b) SCCI, (c) EIRI, and (d) VP. *ld' means leading operating PFs of DGs; T2 = T_2 type of DG.

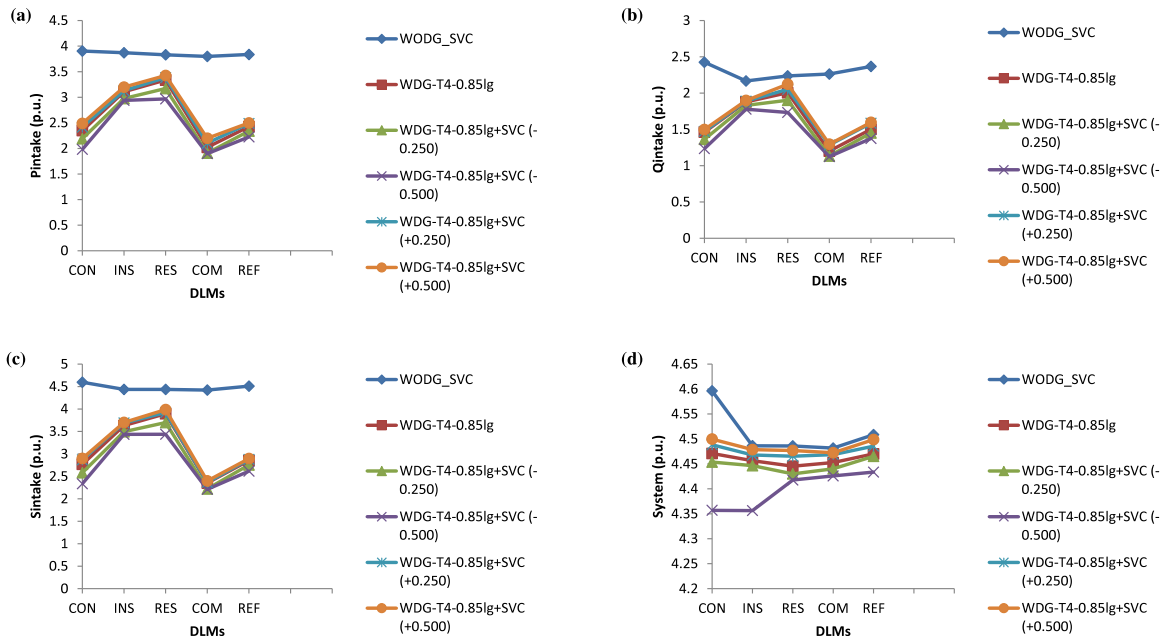


Fig. 19. Pertaining to DG (i.e. T_4 operating at 0.85 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{intake} , (b) Q_{intake} , (c) S_{intake} , and (d) S_{system} . *lg' means lagging operating PFs of DGs; T4 = T_4 type of DG.

- (c) **[Mutation]** With a mutation probability method new offspring mutates (children) at each locus (position in chromosome).
- (d) **[Accepting]** Place new offspring in a new population. It satisfies the constraints such as power flow conservation limits, distribution line thermal capacity limit and voltage deviation limit? Otherwise go to step 6.

7. **[Replacement]** Use new generated population for a further run of algorithm. Run load flow and calculate the new fitness solution for each size–placement pairs of different

types of DG and single FACTS controller like SVC (chromosome). Also calculate the corresponding DPS performance indices such as PLI, QLI, VDI, SCCI, and EIRI. Compare new fitness solution with base case (initial fitness solution) characteristic

8. **[Test]** If one of the stopping criteria is satisfied then stop, and retain the best solution in current population.
9. **[Loop]** Use the new generated population size i.e. offspring and parents as new generation. It satisfies the multi-objective performance indices function (MUOPIF) is minimized? Otherwise, set generation $Gen = Gen + 1$. Go to step 6.

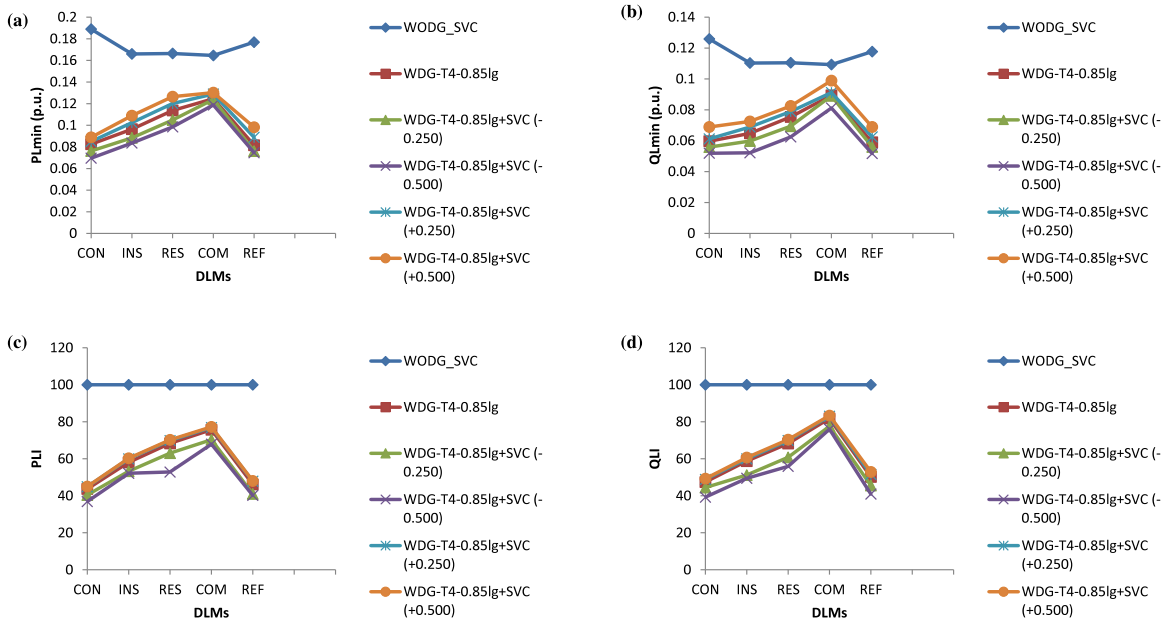


Fig. 20. Pertaining to DG (i.e. T_4 operating at 0.85 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{Lmin} , (b) Q_{Lmin} , (c) PLI , and (d) QLI . ‘‘lg’’ means lagging operating PFs of DGs; $T_4 = T_4$ type of DG.

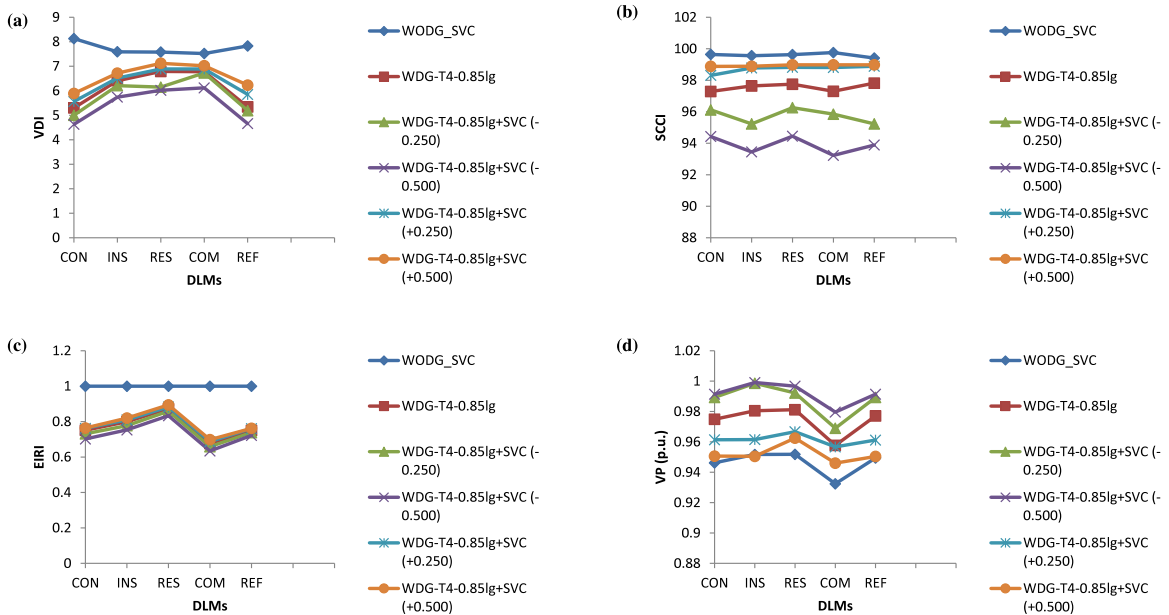


Fig. 21. Pertaining to DG (i.e. T_4 operating at 0.85 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) VDI , (b) $SCCI$, (c) $EIRI$, and (d) VP . ‘‘lg’’ means lagging operating PFs of DGs; $T_4 = T_4$ type of DG.

The flowchart for proposed methodology such as GA for impact assessment of optimally placed different types of DGs and single FACTS controller like SVC with DLMs in DPSS from minimum total MVA intake of main substation viewpoint is given in Fig. 5.

4. Multi-objective function based formulations

The multi-objective index for the PS performance calculation of distribution systems for DG and single FACTS controller like SVC size–placement planning with load models considers all previously mentioned indices by strategically giving a weight. This can be performed since all impact DPS performance indices

were normalized (values between 0 and 1). The GA based multi-objective performance index function (MUOPIF) of this kind of problem is given by Eqs. (34)–(35).

$$MUOPIF = \mu_1 (PLI) + \mu_2 (QLI) + \mu_3 (VDI) + \mu_4 (SCCI) + \mu_5 (EIRI) \tag{34}$$

where

$$\sum_{p=1}^5 \mu_p = 1 \wedge \mu_p \in (0 \ 1) \tag{35}$$

The values of μ_p are based on their importance of DPS performance indices in DPSS. The value of particular μ_p is high when importances of that DPS performance index are of main priority

Table 11DG (i.e. T₂ operating at 0.85 leading power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total MVA intake of main substation viewpoint.

DLMs	WODG_SVC/WDG/WDG+SVC	P _{DG}	Q _{DG}	PF _{DG}	LOC _{DG}	SVC _{alpha}	SVC _{MVAR}	SVC _{LOC}	P _{intake}	Q _{intake}	S _{intake}	S _{System}	P _{Lmin}	Q _{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V _{min}	V _{max}
CON	WODG_SVC	–	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T2-0.85ld/SVC _{alpha=115} ⁰	1.4473	0.8970	0.85	6	–	–	–	2.3501	1.4627	2.7681	4.4709	0.0825	0.0597	43.69	47.42	5.30	96.29	0.9779	0.9749	1.03
	WDG-T2-0.85ld+SVC (–0.250)	1.5452	0.9576	0.85	26	115.44	–0.250	6	2.2462	1.3985	2.6460	4.4639	0.0764	0.0511	40.47	44.61	5.11	95.19	0.9660	0.9793	1.03
	WDG-T2-0.85ld+SVC (–0.500)	1.7446	1.0812	0.85	26	117.09	–0.500	6	2.0401	1.2709	2.4036	4.4561	0.0697	0.0521	36.93	41.38	4.73	94.02	0.9567	0.9814	1.03
	WDG-T2-0.85ld+SVC (+0.250)	1.3543	0.8393	0.85	06	112.25	+0.250	31	2.4473	1.5229	2.8824	4.4758	0.0867	0.0622	45.91	49.45	5.47	98.30	0.9800	0.9714	1.03
	WDG-T2-0.85ld+SVC (+0.500)	1.1738	0.7274	0.85	06	110.71	+0.500	6	2.6370	1.6404	3.1055	4.4965	0.0958	0.0678	50.74	53.89	5.82	98.32	0.9885	0.9706	1.03
INS	WODG_SVC	–	–	–	–	–	–	–	3.8709	2.1673	4.4363	4.4363	0.1660	0.1103	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T2-0.85ld/SVC _{alpha=115} ⁰	0.7004	0.4340	0.85	30	–	–	–	3.1087	1.8789	3.6324	4.4064	0.0964	0.0648	58.06	58.74	6.41	98.45	0.9107	0.9805	1.03
	WDG-T2-0.85ld+SVC (–0.250)	0.8368	0.5186	0.85	30	115.44	–0.250	30	2.9651	1.8272	3.4830	4.3074	0.0878	0.0594	52.87	53.85	6.20	97.01	0.9050	0.9886	1.03
	WDG-T2-0.85ld+SVC (–0.500)	0.8697	0.5390	0.85	13	117.09	–0.500	30	2.9400	1.7785	3.4360	4.11592	0.0863	0.0588	56.41	56.44	5.74	95.89	0.8897	0.9891	1.03
	WDG-T2-0.85ld+SVC (+0.250)	0.1522	0.3174	0.85	29	112.25	+0.250	30	3.3111	1.9446	3.8399	4.4124	0.1129	0.0750	68.01	68.00	6.72	98.87	0.9110	0.9715	1.03
	WDG-T2-0.85ld+SVC (+0.500)	0.4469	0.2769	0.85	28	110.71	+0.500	6	3.3847	1.9599	3.9112	4.4268	0.1222	0.0820	73.64	74.37	6.82	98.97	0.9215	0.9705	1.03
RES	WODG_SVC	–	–	–	–	–	–	–	3.8304	2.2375	4.4360	4.4560	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T2-0.85ld/SVC _{alpha=115} ⁰	0.4680	0.2900	0.85	31	–	–	–	3.3382	2.0061	3.8947	4.4453	0.1137	0.0754	68.33	68.44	6.79	98.58	0.9130	0.9812	1.03
	WDG-T2-0.85ld+SVC (–0.250)	0.6390	0.3960	0.85	14	115.44	–0.250	30	3.1728	1.9041	3.7003	4.4520	0.1047	0.0691	62.95	62.56	6.15	97.40	0.8915	0.9822	1.03
	WDG-T2-0.85ld+SVC (–0.500)	0.8590	0.5324	0.85	24	117.09	–0.500	31	2.9602	1.7362	3.4318	4.4423	0.1002	0.0689	61.98	62.10	6.02	96.96	0.8800	0.9867	1.03
	WDG-T2-0.85ld+SVC (+0.250)	0.3915	0.2426	0.85	30	112.25	+0.250	30	3.4169	2.0411	3.9801	4.4511	0.1218	0.0811	73.24	73.43	6.92	98.90	0.9132	0.9767	1.03
	WDG-T2-0.85ld+SVC (+0.500)	0.3034	0.1880	0.85	29	110.71	+0.500	6	3.5097	2.0814	4.0805	4.4574	0.1322	0.0877	79.46	79.33	7.06	98.96	0.9235	0.9725	1.03
COM	WODG_SVC	–	–	–	–	–	–	–	3.7987	2.2632	4.4217	4.4517	0.1646	0.1093	100	100	7.65	99.76	100	0.9524	1.03
	WDG-T2-0.85ld/SVC _{alpha=115} ⁰	1.7598	1.0906	0.85	23	–	–	–	2.0475	1.2165	2.3816	4.4218	0.1248	0.0894	78.85	81.85	6.79	97.87	0.9121	0.9577	1.03
	WDG-T2-0.85ld+SVC (–0.250)	1.8237	1.1302	0.85	24	115.44	–0.250	30	2.0051	1.2009	2.3373	4.4027	0.1236	0.0810	76.96	83.2	6.77	96.30	0.8815	0.9590	1.03
	WDG-T2-0.85ld+SVC (–0.500)	1.9195	1.1896	0.85	24	117.09	–0.500	30	1.9136	1.1470	2.2310	4.3592	0.1127	0.0789	77.43	84.11	6.73	95.99	0.8501	0.9596	1.03
	WDG-T2-0.85ld+SVC (+0.250)	1.5819	0.9803	0.85	30	112.25	+0.250	29	2.2559	1.4787	2.6973	4.4245	0.1233	0.0792	78.44	85.12	7.01	96.50	0.9124	0.9567	1.03
	WDG-T2-0.85ld+SVC (+0.500)	1.7044	1.0563	0.85	31	110.71	+0.500	29	2.1629	1.4423	2.5997	4.4260	0.1360	0.0885	79.90	86.56	7.51	98.01	0.9226	0.9560	1.03
REF	WODG_SVC	–	–	–	–	–	–	–	3.8369	2.3677	4.5086	4.5086	0.1769	0.1177	100	100	7.53	99.41	100	0.9495	1.03
	WDG-T2-0.85ld/SVC _{alpha=115} ⁰	1.3748	0.8520	0.85	26	–	–	–	2.4252	1.5018	2.8525	4.4400	0.0816	0.0590	46.14	50.19	5.33	98.32	0.9572	0.9771	1.03
	WDG-T2-0.85ld+SVC (–0.250)	1.4591	0.9023	0.85	27	115.44	–0.250	6	2.3446	1.4542	2.7590	4.4019	0.0763	0.0560	43.12	47.60	5.19	95.10	0.9201	0.9793	1.03
	WDG-T2-0.85ld+SVC (–0.500)	1.5652	0.9700	0.85	26	117.09	–0.500	30	2.2356	1.3856	2.6302	4.4017	0.0745	0.0549	42.15	46.64	5.00	92.89	0.9078	0.9814	1.03
	WDG-T2-0.85ld+SVC (+0.250)	1.2168	0.7541	0.85	26	112.25	+0.250	30	2.5835	1.5989	3.0383	4.4409	0.0885	0.0632	50.04	53.75	5.61	98.93	0.9588	0.9712	1.03
	WDG-T2-0.85ld+SVC (+0.500)	0.9856	0.6108	0.85	06	110.71	+0.500	6	2.8177	1.7416	3.3125	4.4433	0.1025	0.0716	57.96	60.82	6.02	98.98	0.9698	0.9704	1.03

Table 12DG (i.e. T₂ operating at 0.90 leading power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total MVA intake of main substation viewpoint.

DLMs	WODG_SVC/WDG/WDG+SVC	P _{DG}	Q _{DG}	PF _{DG}	LOC _{DG}	SVC _{alpha}	SVC _{MVAR}	SVC _{LOC}	P _{intake}	Q _{intake}	S _{intake}	S _{system}	P _{Lmin}	Q _{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V _{min}	V _{max}
CON	WODG_SVC	–	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T2-0.90ld/SVC _{alpha=115} ⁰	2.6687	1.2925	0.90	05	–	–	–	1.1404	1.0835	1.5731	4.4895	0.0942	0.0760	49.87	60.40	5.29	98.29	0.9564	0.9749	1.03
	WDG-T2-0.90ld+SVC (–0.250)	2.6991	1.3072	0.90	05	115.44	–0.250	6	1.1099	1.0687	1.5407	4.4692	0.0940	0.0759	49.75	60.30	5.26	97.29	0.9260	0.9893	1.03
	WDG-T2-0.90ld+SVC (–0.500)	2.6988	1.3071	0.90	06	117.09	–0.500	6	1.0765	1.0399	1.4968	4.4454	0.0603	0.0470	31.94	37.38	3.28	96.25	0.9067	0.9914	1.03
	WDG-T2-0.90ld+SVC (+0.250)	2.4703	1.1964	0.90	06	112.25	+0.250	27	1.3061	1.1510	1.7409	4.4966	0.0614	0.0475	32.54	37.71	3.67	98.38	0.9600	0.9714	1.03
	WDG-T2-0.90ld+SVC (+0.500)	2.2498	1.0896	0.90	27	110.71	+0.500	23	1.5291	1.2590	1.9808	4.5094	0.0639	0.0487	33.86	38.67	4.05	98.69	0.9785	0.9606	1.03
INS	WODG_SVC	–	–	–	–	–	–	–	3.8709	2.1673	4.4363	4.4863	0.1660	0.1103	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T2-0.90ld/SVC _{alpha=115} ⁰	0.7454	0.3610	0.90	30	–	–	–	3.0650	1.9518	3.6337	4.4574	0.0977	0.0658	58.87	59.62	6.42	97.98	0.8907	0.9805	1.03
	WDG-T2-0.90ld+SVC (–0.250)	0.8442	0.4089	0.90	31	115.44	–0.250	30	2.9624	1.9343	3.5380	4.4101	0.0924	0.0625	55.68	56.66	6.28	95.30	0.8600	0.9886	1.03
	WDG-T2-0.90ld+SVC (–0.500)	0.9208	0.4460	0.90	13	117.09	–0.500	30	2.8890	1.8698	3.4413	4.4085	0.0910	0.0624	55.60	56.58	5.75	93.89	0.7497	0.9991	1.03
	WDG-T2-0.90ld+SVC (+0.250)	0.5422	0.2626	0.90	29	112.25	+0.250	6	3.2819	1.9968	3.8426	4.4627	0.1138	0.0757	68.54	68.63	6.73	98.87	0.8910	0.9715	1.03
	WDG-T2-0.90ld+SVC (+0.500)	0.5104	0.2472	0.90	28	110.71	+0.500	6	3.3191	1.9951	3.8726	4.4678	0.1199	0.0806	72.27	73.07	6.77	98.98	0.9015	0.9605	1.03
RES	WODG_SVC	–	–	–	–	–	–	–	3.8304	2.2375	4.4360	4.4560	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T2-0.90ld/SVC _{alpha=115} ⁰	0.5028	0.2435	0.90	31	–	–	–	3.3041	2.0534	3.8902	4.4462	0.1141	0.0758	68.61	68.61	6.79	97.10	0.9040	0.9812	1.03
	WDG-T2-0.90ld+SVC (–0.250)	0.6820	0.3303	0.90	14	115.44	–0.250	30	3.1295	1.9695	3.6977	4.4217	0.1046	0.0690	62.90	62.45	6.15	94.70	0.8225	0.9822	1.03
	WDG-T2-0.90ld+SVC (–0.500)	0.9011	0.4364	0.90	23	117.09	–0.500	27	2.9177	1.8242	3.4410	4.4478	0.1002	0.0668	61.30	61.89	7.22	92.96	0.7010	0.9967	1.03
	WDG-T2-0.90ld+SVC (+0.250)	0.4101	0.1986	0.90	12	112.25	+0.250	6	3.4022	2.0686	3.9817	4.4500	0.1249	0.0828	75.08	74.92	7.52	98.90	0.9142	0.9767	1.03
	WDG-T2-0.90ld+SVC (+0.500)	0.2880	0.1395	0.90	30	110.71	+0.500	6	3.5261	2.1289	4.1189	4.4557	0.1345	0.0895	80.85	80.98	7.61	98.92	0.9255	0.9825	1.03
COM	WODG_SVC	–	–	–	–	–	–	–	3.7987	2.2632	4.4217	4.4817	0.1646	0.1093	100	100	7.52	99.76	100	0.9524	1.03
	WDG-T2-0.90ld/SVC _{alpha=115} ⁰	1.6338	0.7913	0.90	24	–	–	–	2.1840	1.5249	2.6637	4.4655	0.1261	0.0895	76.61	81.87	6.88	97.84	0.9031	0.9577	1.03
	WDG-T2-0.90ld+SVC (–0.250)	1.8588	0.9002	0.90	24	115.44	–0.250	30	1.9671	1.4270	2.4302	4.4582	0.1258	0.0885	76.86	82.86	6.79	95.20	0.8825	0.9690	1.03
	WDG-T2-0.90ld+SVC (–0.500)	2.0693	1.0022	0.90	24	117.09	–0.500	30	1.7654	1.3362	2.2140	4.4315	0.1250	0.0842	75.77	81.54	6.71	93.01	0.7801	0.9796	1.03
	WDG-T2-0.90ld+SVC (+0.250)	1.4703	0.7121	0.90	24	112.25	+0.250	6	2.3424	1.5966	2.8348	4.4572	0.1266	0.0892	76.96	81.61	6.94	98.82	0.9124	0.9667	1.03
	WDG-T2-0.90ld+SVC (+0.500)	1.3186	0.6386	0.90	31	110.71	+0.500	24	2.5096	1.7768	3.0760	4.4676	0.1285	0.0905	77.33	82.77	7.75	98.89	0.9226	0.9760	1.03
REF	WODG_SVC	–	–	–	–	–	–	–	3.8369	2.3677	4.5086	4.5086	0.1769	0.1177	100	100	7.83	99.41	100	0.9494	1.03
	WDG-T2-0.90ld/SVC _{alpha=115} ⁰	1.4566	0.7054	0.90	26	–	–	–	2.3445	1.6491	2.8664	4.4714	0.0830	0.0600	46.93	50.98	5.35	98.78	0.9372	0.9771	1.03
	WDG-T2-0.90ld+SVC (–0.250)	1.6816	0.8144	0.90	27	115.44	–0.250	6	2.1219	1.5448	2.6247	4.4458	0.0739	0.0546	41.78	46.44	4.98	95.10	0.9001	0.9893	1.03
	WDG-T2-0.90ld+SVC (–0.500)	1.6933	0.8201	0.90	26	117.09	–0.500	30	2.1091	1.5368	2.6096	4.4237	0.0735	0.0544	40.50	45.97	4.96	92.00	0.8878	0.9914	1.03
	WDG-T2-0.90ld+SVC (+0.250)	1.3266	0.6425	0.90	06	112.25	+0.250	6	2.4748	1.7103	3.0038	4.4807	0.0901	0.0641	50.93	54.44	5.56	98.94	0.9386	0.9712	1.03
	WDG-T2-0.90ld+SVC (+0.500)	1.0901	0.5279	0.90	06	110.71	+0.500	6	2.7133	1.8248	3.2698	4.4845	0.1011	0.0707	57.16	60.12	5.96	98.98	0.9498	0.9604	1.03

Table 13DG (i.e. T₂ operating at 0.95 leading power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total MVA intake of main substation viewpoint.

DLMs	WODG_SVC/WDG/WDG+SVC	P _{DG}	Q _{DG}	PF _{DG}	LOC _{DG}	SVC _{alpha}	SVC _{MVAR}	SVC _{LOC}	P _{intake}	Q _{intake}	S _{intake}	System	P _{Lmin}	Q _{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V _{min}	V _{max}
CON	WODG_SVC	–	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T2-0.95Id/SVC _{alpha=115} ⁰	1.6347	0.5373	0.95	06	–	–	–	2.1676	1.8255	2.8339	4.4768	0.0874	0.0628	46.28	49.92	5.36	97.30	0.9679	0.9749	1.03
	WDG-T2-0.95Id+SVC (–0.250)	1.8560	0.6100	0.95	06	115.44	–0.250	30	1.9394	1.7486	2.6113	4.4586	0.0704	0.0586	42.58	48.59	5.00	95.29	0.9560	0.9893	1.03
	WDG-T2-0.95Id+SVC (+0.500)	2.0141	0.6620	0.95	06	117.09	–0.500	6	1.7772	1.6942	2.4553	4.4439	0.0663	0.0562	40.43	44.68	4.74	93.01	0.9467	0.9914	1.03
	WDG-T2-0.95Id+SVC (+0.500)	1.4251	0.4684	0.95	06	112.25	+0.250	6	2.3852	1.8993	3.0490	4.4861	0.0954	0.0677	50.53	53.81	5.70	98.30	0.9700	0.9614	1.03
INS	WODG_SVC	–	–	–	–	–	–	–	3.8709	2.1673	4.4363	4.4863	0.1660	0.1103	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T2-0.95Id/SVC _{alpha=115} ⁰	0.7873	0.2587	0.95	30	–	–	–	3.0263	2.0506	3.6556	4.4584	0.0911	0.0681	60.92	61.78	6.45	97.10	0.9007	0.9805	1.03
	WDG-T2-0.95Id+SVC (–0.250)	0.9392	0.3087	0.95	30	115.44	–0.250	6	2.8686	2.0327	3.5158	4.4301	0.0839	0.0637	56.59	57.69	6.24	95.50	0.8900	0.9986	1.03
	WDG-T2-0.95Id+SVC (+0.500)	0.9720	0.3194	0.95	14	117.09	–0.500	29	2.8408	1.9970	3.4725	4.4114	0.0720	0.0617	55.42	56.71	5.79	93.23	0.8797	0.9991	1.03
	WDG-T2-0.95Id+SVC (+0.500)	0.6571	0.2159	0.95	29	112.25	+0.250	6	3.1643	2.0579	3.7746	4.4668	0.1103	0.0737	66.45	66.78	6.63	98.91	0.9110	0.9715	1.03
RES	WODG_SVC	–	–	–	–	–	–	–	3.8304	2.2375	4.4360	4.4860	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T2-0.95Id/SVC _{alpha=115} ⁰	0.5317	0.1747	0.95	31	–	–	–	3.2767	2.1210	3.9033	4.4469	0.1165	0.0774	70.03	70.07	6.80	97.15	0.9030	0.9812	1.03
	WDG-T2-0.95Id+SVC (–0.250)	0.7182	0.2360	0.95	14	115.44	–0.250	6	3.0936	2.0616	3.7176	4.4208	0.0963	0.0710	63.90	63.45	6.18	96.30	0.8815	0.9922	1.03
	WDG-T2-0.95Id+SVC (+0.500)	0.9561	0.3142	0.95	24	117.09	–0.500	30	2.8635	1.9535	3.4664	4.4121	0.0809	0.0643	62.81	62.54	6.05	92.01	0.8700	0.9967	1.03
	WDG-T2-0.95Id+SVC (+0.500)	0.4329	0.1422	0.95	30	112.25	+0.250	6	3.3776	2.1398	3.9984	4.4517	0.1250	0.0834	75.15	75.44	6.94	98.89	0.9132	0.9767	1.03
COM	WODG_SVC	–	–	–	–	–	–	–	3.7987	2.2632	4.4217	4.4817	0.1646	0.1093	100	100	7.52	99.76	100	0.9524	1.03
	WDG-T2-0.95Id/SVC _{alpha=115} ⁰	1.7451	0.5736	0.95	24	–	–	–	2.0736	1.7429	2.7087	4.4664	0.1275	0.0903	77.49	82.69	6.88	97.84	0.9021	0.9877	1.03
	WDG-T2-0.95Id+SVC (–0.250)	1.9743	0.6489	0.95	24	115.44	–0.250	6	1.8523	1.6782	2.4995	4.4488	0.1162	0.0815	76.92	81.75	6.80	95.30	0.8815	0.9890	1.03
	WDG-T2-0.95Id+SVC (+0.500)	2.1922	0.7205	0.95	24	117.09	–0.500	29	1.6432	1.6175	2.3057	4.4319	0.1088	0.0801	75.65	80.23	6.56	92.02	0.8601	0.9996	1.03
	WDG-T2-0.95Id+SVC (+0.500)	1.5387	0.5057	0.95	16	112.25	+0.250	31	2.3495	1.9093	3.0276	4.4773	0.1292	0.0813	76.90	82.40	7.14	98.46	0.9124	0.9767	1.03
REF	WODG_SVC	–	–	–	–	–	–	–	3.8369	2.3677	4.5086	4.5086	0.1646	0.1177	100	100	7.83	99.41	100	0.9494	1.03
	WDG-T2-0.95Id/SVC _{alpha=115} ⁰	1.5575	0.5119	0.95	07	–	–	–	2.2481	1.8401	2.9052	4.4739	0.1275	0.0582	48.83	49.43	5.07	97.09	0.9472	0.9771	1.03
	WDG-T2-0.95Id+SVC (–0.250)	1.6637	0.5468	0.95	27	115.44	–0.250	26	2.1419	1.8127	2.8060	4.4678	0.1162	0.0574	46.19	48.49	4.92	95.47	0.9201	0.9893	1.03
	WDG-T2-0.95Id+SVC (+0.500)	1.6906	0.5556	0.95	08	117.09	–0.500	29	2.1211	1.8009	2.7882	4.4514	0.1088	0.0559	45.93	47.49	4.88	92.16	0.9178	0.9914	1.03
	WDG-T2-0.95Id+SVC (+0.500)	1.3311	0.4375	0.95	07	112.25	+0.250	6	2.4742	1.9127	3.1274	4.4758	0.1292	0.0626	53.41	53.81	5.41	98.91	0.9586	0.9712	1.03
WDG-T2-0.95Id+SVC (+0.500)	1.2355	0.4061	0.95	06	110.71	+0.500	6	2.5689	1.9476	3.2237	4.4887	0.1308	0.0702	56.59	59.67	5.88	98.97	0.9598	0.9504	1.03	

Table 14DG (i.e. T₂ operating at 0.99 leading power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total MVA intake of main substation viewpoint.

DLMs	WODG_SVC/WDG/WDG+SVC	P _{DG}	Q _{DG}	PF _{DG}	LOC _{DG}	SVC _{alpha}	SVC _{MVAR}	SVC _{LOC}	P _{intake}	Q _{intake}	S _{intake}	S _{system}	P _{Lmin}	Q _{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V _{min}	V _{max}
CON	WODG_SVC	–	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T2-0.99ld/SVC _{alpha=115} ⁰	1.8636	0.2655	0.99	06	–	–	–	1.9436	2.1005	2.8618	4.4826	0.0923	0.0611	48.88	52.51	5.29	98.29	0.9679	0.9749	1.03
	WDG-T2-0.99ld+SVC (–0.250)	2.1708	0.3093	0.99	06	115.44	–0.250	30	1.6304	2.0532	2.6218	4.4656	0.0826	0.0606	45.66	49.71	4.84	96.19	0.9560	0.9893	1.03
	WDG-T2-0.99ld+SVC (–0.500)	2.3848	0.3398	0.99	06	117.09	–0.500	30	1.4137	2.0213	2.4666	4.4426	0.0815	0.0601	44.24	48.55	4.53	94.78	0.9367	0.9914	1.03
	WDG-T2-0.99ld+SVC (+0.250)	1.6046	0.2286	0.99	06	112.25	+0.250	27	2.2098	2.1417	3.0774	4.4910	0.0995	0.0704	52.67	55.93	5.68	99.10	0.9800	0.9614	1.03
	WDG-T2-0.99ld+SVC (+0.500)	1.3854	0.1974	0.99	06	110.71	+0.500	27	2.4366	2.1776	3.2679	4.5299	0.1071	0.0750	56.69	59.59	6.00	99.40	0.9885	0.9506	1.03
INS	WODG_SVC	–	–	–	–	–	–	–	3.8709	2.1673	4.4363	4.4863	0.1660	0.1103	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T2-0.99ld/SVC _{alpha=115} ⁰	0.8887	0.1266	0.99	30	–	–	–	2.9292	2.1872	3.6557	4.4643	0.1053	0.0712	63.43	64.56	6.44	98.10	0.9007	0.9805	1.03
	WDG-T2-0.99ld+SVC (–0.250)	1.0122	0.1442	0.99	31	115.44	–0.250	30	2.8045	2.2017	3.5655	4.4401	0.1027	0.0701	61.88	63.57	6.29	96.45	0.8900	0.9886	1.03
	WDG-T2-0.99ld+SVC (–0.500)	1.0129	0.1443	0.99	15	117.09	–0.500	30	2.8074	2.1656	3.5456	4.4244	0.1011	0.0689	60.29	62.99	5.88	93.12	0.8697	0.9991	1.03
	WDG-T2-0.99ld+SVC (+0.250)	0.7554	0.1076	0.99	29	112.25	+0.250	6	3.0676	2.1714	3.7584	4.4709	0.1119	0.0750	67.39	67.97	6.60	98.83	0.9110	0.9715	1.03
	WDG-T2-0.99ld+SVC (+0.500)	0.5824	0.0832	0.99	09	110.71	+0.500	6	3.2476	2.1411	3.8899	4.4807	0.1122	0.0807	73.60	73.13	6.70	99.03	0.9215	0.9605	1.03
RES	WODG_SVC	–	–	–	–	–	–	–	3.8304	2.2375	4.4360	4.4860	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T2-0.99ld/SVC _{alpha=115} ⁰	0.5649	0.0805	0.99	14	–	–	–	3.2476	2.1958	3.9203	4.4404	0.1190	0.0782	71.53	70.80	6.47	98.20	0.9030	0.9812	1.03
	WDG-T2-0.99ld+SVC (–0.250)	0.7693	0.1096	0.99	14	115.44	–0.250	30	3.0446	2.1864	3.7483	4.4317	0.1101	0.0727	66.22	65.82	6.22	97.40	0.8915	0.9822	1.03
	WDG-T2-0.99ld+SVC (–0.500)	0.9020	0.1285	0.99	15	117.09	–0.500	30	2.9168	2.8138	3.6437	4.4144	0.1078	0.0719	64.82	65.04	6.06	95.22	0.8700	0.9967	1.03
	WDG-T2-0.99ld+SVC (+0.250)	0.5174	0.0737	0.99	12	112.25	+0.250	6	3.2949	2.1953	3.9592	4.4465	0.1239	0.0821	74.52	74.31	6.53	98.82	0.9132	0.9767	1.03
	WDG-T2-0.99ld+SVC (+0.500)	0.3762	0.0536	0.99	30	110.71	+0.500	6	3.4387	2.2184	4.0922	4.4502	0.1340	0.0893	80.58	80.82	7.08	99.04	0.9235	0.9625	1.03
COM	WODG_SVC	–	–	–	–	–	–	–	3.7987	2.2632	4.4217	4.4817	0.1646	0.1093	100	100	7.52	99.76	100	0.9524	1.03
	WDG-T2-0.99ld/SVC _{alpha=115} ⁰	1.9812	0.2823	0.99	23	–	–	–	1.8271	2.0219	2.7251	4.4512	0.1304	0.0922	79.24	84.42	6.85	97.11	0.9021	0.9777	1.03
	WDG-T2-0.99ld+SVC (–0.250)	2.9477	0.4200	0.99	24	115.44	–0.250	31	0.9208	1.9514	2.1577	4.4175	0.1282	0.0898	78.70	83.67	6.54	95.45	0.8815	0.9890	1.03
	WDG-T2-0.99ld+SVC (–0.500)	2.9626	0.4221	0.99	23	117.09	–0.500	31	0.8681	1.9126	2.1004	4.4062	0.1214	0.0865	77.83	82.29	6.12	92.79	0.8501	0.9996	1.03
	WDG-T2-0.99ld+SVC (+0.250)	0.4056	0.0577	0.99	15	112.25	+0.250	28	3.3913	2.2239	4.0555	4.4598	0.1282	0.0873	77.88	83.18	6.66	98.45	0.9124	0.9667	1.03
	WDG-T2-0.99ld+SVC (+0.500)	1.7359	0.2473	0.99	13	110.71	+0.500	31	2.1451	2.1593	3.0437	4.4667	0.1335	0.0915	78.86	85.09	7.08	98.50	0.9226	0.9560	1.03
REF	WODG_SVC	–	–	–	–	–	–	–	3.8369	2.3677	4.5086	4.5086	0.1769	0.1177	100	100	7.83	99.41	100	0.9494	1.03
	WDG-T2-0.99ld/SVC _{alpha=115} ⁰	1.6624	0.2368	0.99	27	–	–	–	2.1488	2.1250	3.0110	4.4837	0.0934	0.0666	52.81	56.59	5.48	97.23	0.9472	0.9771	1.03
	WDG-T2-0.99ld+SVC (–0.250)	1.8209	0.2594	0.99	27	115.44	–0.250	30	1.9924	2.1048	2.8983	4.4469	0.0903	0.0647	51.07	55.01	5.27	96.98	0.9301	0.9793	1.03
	WDG-T2-0.99ld+SVC (–0.500)	1.9053	0.2714	0.99	08	117.09	–0.500	30	1.9149	2.0913	2.8356	4.4219	0.0892	0.0617	50.47	52.42	4.85	93.07	0.9178	0.9814	1.03
	WDG-T2-0.99ld+SVC (+0.250)	1.5499	0.2208	0.99	26	112.25	+0.250	27	2.2589	2.1376	3.1100	4.4899	0.0971	0.0687	54.90	59.40	5.63	98.24	0.9586	0.9712	1.03
	WDG-T2-0.99ld+SVC (+0.500)	1.2875	0.1834	0.99	07	110.71	+0.500	6	2.2515	2.1686	3.3285	4.4967	0.1051	0.0711	59.40	61.19	5.78	98.85	0.9598	0.9604	1.03

Table 15DG (i.e. T₄ operating at 0.85 lagging power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total MVA intake of main substation viewpoint.

DLMs	WODG_SVC/WDG/WDG+SVC	P _{DG}	Q _{DG}	PF _{DG}	LOC _{DG}	SVC _{alpha}	SVC _{MVAR}	SVC _{LOC}	P _{intake}	Q _{intake}	S _{intake}	S _{System}	P _{Lmin}	Q _{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V _{min}	V _{max}
CON	WODG_SVC	–	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T4-0.85lg/SVC _{alpha=115} ⁰	1.4473	0.8970	0.85	6	–	–	–	2.3501	1.4627	2.7681	4.4709	0.0825	0.0597	43.69	47.42	5.30	97.29	0.7514	0.9749	1.03
	WDG-T4-0.85lg+SVC (–0.250)	1.6007	0.9920	0.85	6	115.44	–0.250	6	2.1906	1.3639	2.5805	4.4537	0.0763	0.0559	40.43	44.45	5.00	96.12	0.7314	0.9893	1.03
	WDG-T4-0.85lg+SVC (–0.500)	1.8021	1.1168	0.85	6	117.09	–0.500	6	1.9824	1.2350	2.3357	4.3569	0.0696	0.0519	36.87	39.25	4.63	94.43	0.7019	0.9914	1.03
	WDG-T4-0.85lg+SVC (+0.250)	1.3169	0.8161	0.85	5	112.25	+0.250	6	2.4176	1.4736	2.8689	4.4883	0.0850	0.0612	44.89	48.85	5.56	98.31	0.7625	0.9614	1.03
	WDG-T4-0.85lg+SVC (+0.500)	1.1697	0.7249	0.85	6	110.71	+0.500	30	2.4896	1.4985	2.8987	4.4996	0.0889	0.0689	44.99	49.25	5.89	98.88	0.7640	0.9506	1.03
INS	WODG_SVC	–	–	–	–	–	–	–	3.8709	2.1673	4.4363	4.4863	0.1660	0.1103	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T4-0.85lg/SVC _{alpha=115} ⁰	0.7004	0.4341	0.85	30	–	–	–	3.1087	1.8789	3.6324	4.4564	0.0964	0.0648	58.06	58.74	6.41	97.64	0.7995	0.9805	1.03
	WDG-T4-0.85lg+SVC (–0.250)	0.8261	0.5119	0.85	30	115.44	–0.250	30	2.9764	1.8312	3.4946	4.4465	0.0884	0.0598	53.26	51.21	6.21	95.23	0.7775	0.9986	1.03
	WDG-T4-0.85lg+SVC (–0.500)	0.8697	0.5390	0.85	13	117.09	–0.500	30	2.9400	1.7785	3.4360	4.3564	0.0836	0.0522	52.16	49.44	5.74	93.45	0.7532	0.9991	1.03
	WDG-T4-0.85lg+SVC (+0.250)	0.5614	0.3479	0.85	29	112.25	+0.250	6	3.1298	1.8896	3.6895	4.4678	0.1025	0.0689	59.98	59.96	6.52	98.78	0.8098	0.9615	1.03
	WDG-T4-0.85lg+SVC (+0.500)	0.4469	0.2769	0.85	28	110.71	+0.500	6	3.1989	1.8989	3.7003	4.4786	0.1089	0.0725	60.25	60.65	6.72	98.89	0.8199	0.9505	1.03
RES	WODG_SVC	–	–	–	–	–	–	–	3.8304	2.2375	4.4360	4.4860	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T4-0.85lg/SVC _{alpha=115} ⁰	0.4680	0.2900	0.85	31	–	–	–	3.3382	2.0061	3.8947	4.4454	0.1137	0.0754	68.33	68.24	6.79	97.75	0.8730	0.9812	1.03
	WDG-T4-0.85lg+SVC (–0.250)	0.6390	0.3960	0.85	13	115.44	–0.250	30	3.1716	1.9020	3.6982	4.4300	0.1049	0.0694	63.04	60.78	6.15	96.26	0.8589	0.9922	1.03
	WDG-T4-0.85lg+SVC (–0.500)	0.8506	0.5272	0.85	23	117.09	–0.500	31	2.9681	1.7334	3.4372	4.4177	0.0985	0.0625	52.85	55.89	6.02	94.45	0.8334	0.9967	1.03
	WDG-T4-0.85lg+SVC (+0.250)	0.2697	0.1671	0.85	31	112.25	+0.250	6	3.3856	2.0523	3.9213	4.4654	0.1201	0.0789	69.86	69.89	6.89	98.82	0.8833	0.9667	1.03
	WDG-T4-0.85lg+SVC (+0.500)	0.2558	0.1585	0.85	29	110.71	+0.500	6	3.4256	2.1235	3.9865	4.4768	0.1265	0.0825	70.23	70.36	7.12	98.98	0.8945	0.9625	1.03
COM	WODG_SVC	–	–	–	–	–	–	–	3.7987	2.2632	4.4217	4.4817	0.1646	0.1093	100	100	7.52	99.76	100	0.9324	1.03
	WDG-T4-0.85lg/SVC _{alpha=115} ⁰	1.7856	1.1066	0.85	23	–	–	–	2.0223	1.2014	2.3522	4.4527	0.1246	0.0894	75.72	81.79	6.78	97.30	0.6765	0.9577	1.03
	WDG-T4-0.85lg+SVC (–0.250)	1.9011	1.1782	0.85	23	115.44	–0.250	31	1.9090	1.1338	2.2203	4.4402	0.1239	0.0891	70.28	77.55	6.73	95.85	0.6589	0.9690	1.03
	WDG-T4-0.85lg+SVC (–0.500)	1.9195	1.1896	0.85	24	117.09	–0.500	30	1.8985	1.1247	2.2109	4.4259	0.1188	0.0812	67.89	75.98	6.12	93.23	0.6343	0.9796	1.03
	WDG-T4-0.85lg+SVC (+0.250)	1.6590	1.0281	0.85	31	112.25	+0.250	27	2.1035	1.2854	2.3658	4.4686	0.1289	0.0912	76.89	82.98	6.89	98.81	0.6871	0.9567	1.03
	WDG-T4-0.85lg+SVC (+0.500)	0.9054	0.5611	0.85	31	110.71	+0.500	6	2.1986	1.2963	2.3986	4.4723	0.1302	0.0989	77.23	83.36	7.02	98.98	0.6981	0.9460	1.03
REF	WODG_SVC	–	–	–	–	–	–	–	3.8369	2.3677	4.5086	4.5086	0.1769	0.1177	100	100	7.83	99.41	100	0.9494	1.03
	WDG-T4-0.85lg/SVC _{alpha=115} ⁰	1.3748	0.8520	0.85	26	–	–	–	2.4252	1.5018	2.8525	4.4700	0.0816	0.0590	46.14	50.19	5.34	97.82	0.7505	0.9771	1.03
	WDG-T4-0.85lg+SVC (–0.250)	1.4595	0.0904	0.85	27	115.44	–0.250	26	2.3411	1.4520	2.7548	4.4653	0.0761	0.0560	41.02	45.56	5.19	95.23	0.7381	0.9893	1.03
	WDG-T4-0.85lg+SVC (–0.500)	1.5793	0.9788	0.85	7	117.09	–0.500	30	2.2254	1.3745	2.6156	4.4336	0.0747	0.0517	40.23	40.92	4.66	93.89	0.7221	0.9914	1.03
	WDG-T4-0.85lg+SVC (+0.250)	1.2296	0.76209	0.85	26	112.25	+0.250	6	2.4896	1.5852	2.8785	4.4856	0.0889	0.0625	47.85	51.56	5.85	98.89	0.7608	0.9612	1.03
	WDG-T4-0.85lg+SVC (+0.500)	1.1015	0.6826	0.85	6	110.71	+0.500	6	2.4986	1.5968	2.8963	4.4987	0.0982	0.0689	48.03	52.89	6.23	98.98	0.7623	0.9504	1.03

Table 16
 DG (i.e. T₄ operating at 0.90 lagging power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total MVA intake of main substation viewpoint.

DLMs	WODG_SVC/WDG/WDG+SVC	P _{DG}	Q _{DG}	PF _{DG}	LOC _{DG}	SVC _{alpha}	SVC _{MVAR}	SVC _{LOC}	P _{intake}	Q _{intake}	S _{intake}	S _{System}	P _{Lmin}	Q _{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V _{min}	V _{max}
CON	WODG_SVC	-	-	-	-	-	-	-	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T4-0.90lg/SVC _{alpha=115} ⁰	1.5446	0.74811	0.90	6	-	-	-	2.2538	1.6122	2.7711	4.4721	0.0835	0.0603	44.20	47.93	5.29	97.29	0.7514	0.9749	1.03
	WDG-T4-0.90lg+SVC (-0.250)	1.6046	0.7771	0.90	27	115.44	-0.250	6	2.1875	1.5796	2.6982	4.4648	0.0771	0.0568	40.82	45.10	5.18	96.02	0.7314	0.9893	1.03
	WDG-T4-0.90lg+SVC (-0.500)	1.9005	0.9204	0.90	26	117.09	-0.500	6	1.8847	1.4320	2.3671	4.4321	0.0703	0.0425	37.22	41.70	4.66	95.45	0.7019	0.9914	1.03
	WDG-T4-0.90lg+SVC (+0.250)	1.4780	0.7158	0.90	6	112.25	+0.250	30	2.2731	1.6461	2.7854	4.4853	0.0962	0.0690	45.85	48.02	5.41	98.56	0.7625	0.9614	1.03
	WDG-T4-0.90lg+SVC (+0.500)	1.2472	0.6040	0.90	6	110.71	+0.500	31	2.3646	1.6984	2.7968	4.4987	0.0998	0.0725	46.12	48.65	5.89	98.89	0.7640	0.9506	1.03
INS	WODG_SVC	-	-	-	-	-	-	-	3.8709	2.1673	4.4363	4.4963	0.1660	0.1103	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T4-0.90lg/SVC _{alpha=115} ⁰	0.7454	0.3610	0.90	30	-	-	-	3.0650	1.9518	3.6337	4.4774	0.0977	0.0658	58.87	56.62	6.42	97.78	0.7895	0.9805	1.03
	WDG-T4-0.90lg+SVC (-0.250)	0.8822	0.4273	0.90	30	115.44	-0.250	29	2.9218	1.9165	3.4943	4.4682	0.0900	0.0610	54.24	55.30	6.21	95.12	0.7775	0.9986	1.03
	WDG-T4-0.90lg+SVC (-0.500)	0.9208	0.4460	0.90	13	117.09	-0.500	30	2.889	1.8698	3.4413	4.4585	0.0870	0.0585	53.03	55.01	5.75	94.45	0.7632	0.9991	1.03
	WDG-T4-0.90lg+SVC (+0.250)	0.5422	0.2626	0.90	29	112.25	+0.250	6	3.1543	1.9686	3.6854	4.4821	0.1025	0.0710	59.46	57.26	6.73	98.87	0.7998	0.9615	1.03
	WDG-T4-0.90lg+SVC (+0.500)	0.5063	0.2452	0.90	28	110.71	+0.500	6	3.2456	1.9987	3.6968	4.4885	0.1198	0.0793	60.86	57.89	6.89	98.94	0.8099	0.9505	1.03
RES	WODG_SVC	-	-	-	-	-	-	-	3.8304	2.2375	4.4360	4.4960	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T4-0.90lg/SVC _{alpha=115} ⁰	0.5542	0.2684	0.90	31	-	-	-	3.2516	2.0356	3.8362	4.4489	0.1102	0.0733	66.26	66.35	6.71	97.81	0.8730	0.9812	1.03
	WDG-T4-0.90lg+SVC (-0.250)	0.6767	0.3277	0.90	14	115.44	-0.250	29	3.1348	1.9715	3.7032	4.4313	0.1049	0.0692	63.06	62.59	6.16	95.06	0.8689	0.9922	1.03
	WDG-T4-0.90lg+SVC (-0.500)	0.8015	0.3882	0.90	15	117.09	-0.500	30	3.0140	1.9287	3.5783	4.4005	0.0906	0.0569	57.50	60.58	5.98	93.56	0.8334	0.9967	1.03
	WDG-T4-0.90lg+SVC (+0.250)	0.4141	0.2005	0.90	30	112.25	+0.250	6	3.2875	2.0829	3.8652	4.4653	0.1089	0.0781	66.98	67.23	6.92	98.89	0.8833	0.9667	1.03
	WDG-T4-0.90lg+SVC (+0.500)	0.2880	0.1395	0.90	30	110.71	+0.500	6	3.2969	2.1003	3.9005	4.4796	0.1103	0.0805	67.12	67.89	7.05	98.96	0.8845	0.9525	1.03
COM	WODG_SVC	-	-	-	-	-	-	-	3.7987	2.2632	4.4217	4.4817	0.1646	0.1093	100	100	7.52	99.76	100	0.9524	1.03
	WDG-T4-0.90lg/SVC _{alpha=115} ⁰	1.6105	0.7800	0.90	24	-	-	-	2.2065	1.5351	2.6880	4.4643	0.1261	0.0894	76.64	81.78	6.89	97.84	0.6775	0.9877	1.03
	WDG-T4-0.90lg+SVC (-0.250)	1.6909	0.8189	0.90	24	115.44	-0.250	30	2.1289	1.5000	2.6042	4.4231	0.1202	0.0812	75.03	81.04	6.23	96.15	0.6689	0.9890	1.03
	WDG-T4-0.90lg+SVC (-0.500)	1.9426	0.9408	0.90	23	117.09	-0.500	27	1.8665	1.3691	2.3147	4.4113	0.1054	0.0754	74.68	80.74	6.02	94.45	0.6333	0.9996	1.03
	WDG-T4-0.90lg+SVC (+0.250)	1.4409	0.6979	0.90	24	112.25	+0.250	29	2.2709	1.5981	2.6993	4.4752	0.1268	0.0903	77.06	81.89	6.95	98.92	0.6878	0.9667	1.03
	WDG-T4-0.90lg+SVC (+0.500)	1.3700	0.6635	0.90	23	110.71	+0.500	23	2.3102	1.6005	2.7009	4.4704	0.1398	0.0983	78.82	82.02	7.06	99.25	0.6881	0.9560	1.03
REF	WODG_SVC	-	-	-	-	-	-	-	3.8369	2.3677	4.5086	4.5086	0.1769	0.1177	100	100	7.83	99.41	100	0.9494	1.03
	WDG-T4-0.90lg/SVC _{alpha=115} ⁰	1.4557	0.7050	0.90	26	-	-	-	2.3454	1.6495	2.8674	4.4714	0.0831	0.0600	46.97	51.02	5.35	97.12	0.7507	0.9771	1.03
	WDG-T4-0.90lg+SVC (-0.250)	1.5222	0.7372	0.90	27	115.44	-0.250	26	2.2797	1.6199	2.7966	4.4625	0.0787	0.0576	41.49	48.92	5.24	96.84	0.7383	0.9893	1.03
	WDG-T4-0.90lg+SVC (-0.500)	1.6947	0.8207	0.90	27	117.09	-0.500	30	2.1090	1.5387	2.6107	4.4321	0.0635	0.0444	38.59	46.27	4.96	94.02	0.7132	0.9914	1.03
	WDG-T4-0.90lg+SVC (+0.250)	1.3102	0.6345	0.90	26	112.25	+0.250	6	2.3911	1.6985	2.8963	4.4885	0.0989	0.0635	47.25	51.84	5.59	98.45	0.7618	0.9612	1.03
	WDG-T4-0.90lg+SVC (+0.500)	1.0774	0.5218	0.90	26	110.71	+0.500	6	2.4008	1.7006	2.9007	4.4908	0.1002	0.0789	48.89	52.29	6.03	98.89	0.7623	0.9504	1.03

Table 17DG (i.e. T₄ operating at 0.95 lagging power factor) and SVC planned by GA with DLMs (such as CON-INS-RES-COM-REF) in DPSs from minimum total MVA intake of main substation viewpoint.

DLMs	WODG_SVC/WDG/WDG+SVC	P _{DG}	Q _{DG}	PF _{DG}	LOC _{DG}	SVC _{alpha}	SVC _{MVAR}	SVC _{LOC}	P _{Intake}	Q _{Intake}	S _{Intake}	System	P _{Lmin}	Q _{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V _{min}	V _{max}
CON	WODG_SVC	–	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T4-0.95lg/SVC _{alpha=115} ⁰	1.6347	0.5373	0.95	06	–	–	–	2.1676	1.8255	2.8339	4.4768	0.0874	0.0628	46.28	49.92	5.36	97.30	0.7513	0.9749	1.03
	WDG-T4-0.95lg+SVC (–0.250)	1.7187	0.5649	0.95	06	115.44	–0.250	6	2.0808	1.7962	2.7489	4.4735	0.0846	0.0611	44.78	48.57	5.22	96.20	0.7313	0.9893	1.03
	WDG-T4-0.95lg+SVC (+0.500)	2.1749	0.7148	0.95	06	117.09	–0.500	6	1.6131	1.6394	2.2999	4.4600	0.0730	0.0543	38.65	43.13	4.48	95.10	0.7018	0.9914	1.03
	WDG-T4-0.95lg+SVC (+0.250)	1.4251	0.4684	0.95	06	112.25	+0.250	27	2.3852	1.8993	3.0490	4.4861	0.0954	0.0677	50.53	53.81	5.70	98.30	0.7622	0.9614	1.03
	WDG-T4-0.95lg+SVC (+0.500)	1.1766	0.3867	0.95	06	110.71	+0.500	6	2.6451	1.9879	3.3089	4.4995	0.1067	0.0747	56.53	59.32	6.12	98.60	0.7641	0.9506	1.03
INS	WODG_SVC	–	–	–	–	–	–	–	3.8709	2.1673	4.4363	4.4363	0.1660	0.1103	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T4-0.95lg/SVC _{alpha=115} ⁰	0.7868	0.2586	0.95	30	–	–	–	3.0268	2.0507	3.6561	4.4584	0.1012	0.0682	60.94	61.81	6.45	97.25	0.7995	0.9805	1.03
	WDG-T4-0.95lg+SVC (–0.250)	0.9392	0.3087	0.95	30	115.44	–0.250	6	2.8686	2.0327	3.5158	4.4701	0.0939	0.0637	56.59	57.76	6.24	96.89	0.7875	0.9986	1.03
	WDG-T4-0.95lg+SVC (+0.500)	0.9720	0.3194	0.95	14	117.09	–0.500	30	2.8408	1.9970	3.4725	4.4614	0.0920	0.0627	55.42	56.71	5.79	94.40	0.7532	0.9991	1.03
	WDG-T4-0.95lg+SVC (+0.250)	0.6698	0.2201	0.95	29	112.25	+0.250	6	3.1509	2.0561	3.7624	4.4474	0.1095	0.0731	65.98	66.31	6.61	98.42	0.8098	0.9615	1.03
	WDG-T4-0.95lg+SVC (+0.500)	0.5606	0.1842	0.95	28	110.71	+0.500	6	3.2690	2.0594	3.8637	4.4386	0.1200	0.0807	72.30	73.19	6.76	98.86	0.8199	0.9505	1.03
RES	WODG_SVC	–	–	–	–	–	–	–	3.8304	2.2375	4.4360	4.4360	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T4-0.95lg/SVC _{alpha=115} ⁰	0.5806	0.1908	0.95	30	–	–	–	3.2262	2.1088	3.8543	4.4475	0.1141	0.0764	68.61	69.10	6.73	97.10	0.8740	0.9812	1.03
	WDG-T4-0.95lg+SVC (–0.250)	0.7182	0.2360	0.95	14	115.44	–0.250	6	3.0936	2.0616	3.7176	4.4508	0.1063	0.0701	63.90	63.45	6.18	95.67	0.8579	0.9922	1.03
	WDG-T4-0.95lg+SVC (+0.500)	0.8460	0.2780	0.95	16	117.09	–0.500	30	2.9726	2.0389	3.6046	4.4666	0.1045	0.0696	62.85	63.03	6.01	93.34	0.8444	0.9967	1.03
	WDG-T4-0.95lg+SVC (+0.250)	0.4332	0.1424	0.95	30	112.25	+0.250	30	3.3772	2.1393	3.9980	4.4417	0.1250	0.0833	75.13	75.42	6.94	98.68	0.8843	0.9667	1.03
	WDG-T4-0.95lg+SVC (+0.500)	0.3304	0.1086	0.95	30	110.71	+0.500	6	3.4836	2.1620	4.1000	4.4388	0.1335	0.0888	80.25	80.40	7.09	98.83	0.8955	0.9525	1.03
COM	WODG_SVC	–	–	–	–	–	–	–	3.7987	2.2632	4.4217	4.4217	0.1646	0.1093	100	100	7.52	99.76	100	0.9524	1.03
	WDG-T4-0.95lg/SVC _{alpha=115} ⁰	1.7163	0.5641	0.95	24	–	–	–	2.1014	1.7510	2.7354	4.4649	0.1275	0.0902	77.50	82.56	6.89	97.84	0.6765	0.9777	1.03
	WDG-T4-0.95lg+SVC (–0.250)	1.8793	0.6177	0.95	24	115.44	–0.250	31	1.9439	1.7048	2.5856	4.4735	0.1248	0.0900	77.33	81.24	6.83	96.87	0.6489	0.9890	1.03
	WDG-T4-0.95lg+SVC (+0.500)	2.0921	0.6876	0.95	06	117.09	–0.500	24	1.7287	1.8699	2.4175	4.5002	0.0730	0.0540	44.38	49.44	4.52	94.12	0.6143	0.9996	1.03
	WDG-T4-0.95lg+SVC (+0.250)	1.4946	0.4912	0.95	31	112.25	+0.250	29	2.3453	1.9397	3.0435	4.5447	0.0852	0.0613	51.75	56.14	5.48	98.15	0.6871	0.9667	1.03
	WDG-T4-0.95lg+SVC (+0.500)	1.3142	0.4319	0.95	24	110.71	+0.500	23	2.4927	1.8667	3.1142	4.4471	0.1296	0.0902	78.78	82.57	7.03	98.80	0.6981	0.9560	1.03
REF	WODG_SVC	–	–	–	–	–	–	–	3.8369	2.3677	4.5086	4.5086	0.1769	0.1177	100	100	7.83	99.41	100	0.9494	1.03
	WDG-T4-0.95lg/SVC _{alpha=115} ⁰	1.5533	0.5105	0.95	26	–	–	–	2.2505	1.8456	2.9105	4.4745	0.0865	0.0622	48.92	52.84	5.39	97.23	0.7515	0.9771	1.03
	WDG-T4-0.95lg+SVC (–0.250)	1.6760	0.5509	0.95	27	115.44	–0.250	6	2.1297	1.8088	2.7942	4.4780	0.0814	0.0592	46.02	50.35	5.21	95.70	0.7271	0.9893	1.03
	WDG-T4-0.95lg+SVC (+0.500)	1.7634	0.5796	0.95	06	117.09	–0.500	6	2.0408	1.7768	2.7059	4.4750	0.0811	0.0591	45.98	50.22	5.07	93.56	0.6911	0.9914	1.03
	WDG-T4-0.95lg+SVC (+0.250)	1.4133	0.4645	0.95	26	112.25	+0.250	6	2.3903	1.8907	3.0477	4.4738	0.0913	0.0651	51.65	55.32	5.60	98.60	0.7678	0.9612	1.03
	WDG-T4-0.95lg+SVC (+0.500)	1.2891	0.4237	0.95	06	110.71	+0.500	30	2.5149	1.9300	3.1702	4.4734	0.0978	0.0688	55.30	58.49	5.79	98.89	0.7783	0.9504	1.03

Table 18
 DG (i.e. T₄ operating at 0.99 lag power factor) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF) in DPSs from minimum total MVA intake of main substation viewpoint.

DLMs	WODG_SVC/WDG/WDG+SVC	P _{DG}	Q _{DG}	PF _{DG}	LOC _{DG}	SVC _{alpha}	SVC _{MVAR}	SVC _{LOC}	P _{intake}	Q _{intake}	S _{intake}	S _{System}	P _{Lmin}	Q _{Lmin}	PLI	QLI	VDI	SCCI	EIRI	V _{min}	V _{max}
CON	WODG_SVC	–	–	–	–	–	–	–	3.9039	2.4259	4.5962	4.5962	0.1889	0.1259	100	100	8.13	99.64	100	0.9462	1.03
	WDG-T4-0.99lg/SVC _{alpha=115} ⁰	1.7035	0.2427	0.99	26	–	–	–	2.1068	2.1253	2.9926	4.4863	0.0954	0.0680	50.53	54.04	5.53	97.30	0.7524	0.9749	1.03
	WDG-T4-0.99lg+SVC (–0.250)	1.9359	0.2758	0.99	06	115.44	–0.250	26	1.8697	2.0893	2.8037	4.4507	0.0906	0.0651	47.99	51.73	5.19	95.19	0.7324	0.9893	1.03
	WDG-T4-0.99lg+SVC (–0.500)	2.0986	0.2990	0.99	07	117.09	–0.500	26	1.7032	2.0626	2.6749	4.4356	0.0868	0.0616	45.95	48.95	4.63	93.89	0.7029	0.9914	1.03
	WDG-T4-0.99lg+SVC (+0.250)	1.5862	0.2260	0.99	06	112.25	+0.250	6	2.2288	2.1447	3.0931	4.4917	0.1009	0.0707	52.98	56.20	5.70	98.30	0.7635	0.9614	1.03
	WDG-T4-0.99lg+SVC (+0.500)	1.3260	0.1889	0.99	06	110.71	+0.500	6	2.4983	2.1875	3.3207	4.5026	0.1094	0.0764	57.91	60.70	6.09	98.60	0.7750	0.9506	1.03
INS	WODG_SVC	–	–	–	–	–	–	–	3.8709	2.2673	4.4363	4.4863	0.1660	0.1103	100	100	7.59	99.56	100	0.9517	1.03
	WDG-T4-0.99lg/SVC _{alpha=115} ⁰	0.8887	0.1266	0.99	30	–	–	–	2.9292	2.1872	3.6557	4.4643	0.1053	0.0712	63.43	64.56	6.44	97.29	0.7995	0.9805	1.03
	WDG-T4-0.99lg+SVC (–0.250)	0.9955	0.1418	0.99	12	115.44	–0.250	30	2.8200	2.1462	3.5438	4.4290	0.1015	0.0673	61.16	61.03	5.88	95.10	0.7575	0.9886	1.03
	WDG-T4-0.99lg+SVC (–0.500)	1.0129	0.1443	0.99	15	117.09	–0.500	30	2.8074	2.1056	3.5456	4.4044	0.1011	0.0666	60.29	60.99	5.44	92.60	0.7232	0.9991	1.03
	WDG-T4-0.99lg+SVC (+0.250)	0.7381	0.1051	0.99	29	112.25	+0.250	30	3.0856	2.1910	3.7728	4.4656	0.1127	0.0755	67.88	68.47	6.62	98.62	0.8098	0.9615	1.03
	WDG-T4-0.99lg+SVC (+0.500)	0.6343	0.0903	0.99	28	110.71	+0.500	6	3.1962	2.2055	3.8551	4.4785	0.1208	0.0814	72.78	73.78	6.74	98.87	0.8199	0.9542	1.03
RES	WODG_SVC	–	–	–	–	–	–	–	3.8304	2.2375	4.4360	4.4860	0.1664	0.1105	100	100	7.58	99.63	100	0.9518	1.03
	WDG-T4-0.99lg/SVC _{alpha=115} ⁰	0.5451	0.0776	0.99	14	–	–	–	3.2675	2.1968	3.9373	4.4596	0.1200	0.0790	72.16	71.48	6.50	97.49	0.8740	0.9812	1.03
	WDG-T4-0.99lg+SVC (–0.250)	0.7782	0.1108	0.99	14	115.44	–0.250	14	3.0358	2.1661	3.7410	4.4223	0.1098	0.0726	66.01	65.68	6.31	95.97	0.8499	0.9822	1.03
	WDG-T4-0.99lg+SVC (–0.500)	0.9116	0.1299	0.99	16	117.09	–0.500	6	2.9103	2.1261	3.6399	4.4090	0.1069	0.0714	65.45	65.45	6.05	93.30	0.8144	0.9967	1.03
	WDG-T4-0.99lg+SVC (+0.250)	0.5219	0.0742	0.99	12	112.25	+0.250	6	3.2903	2.2050	3.9553	4.4666	0.1236	0.0819	74.34	74.14	6.53	98.40	0.8843	0.9667	1.03
	WDG-T4-0.99lg+SVC (+0.500)	0.3762	0.0536	0.99	30	110.71	+0.500	6	3.4387	2.2185	4.0922	4.4702	0.1340	0.0893	80.58	80.82	7.08	98.84	0.8955	0.9525	1.03
COM	WODG_SVC	–	–	–	–	–	–	–	3.7987	2.2632	4.4217	4.4817	0.1646	0.1093	100	100	7.52	99.76	100	0.9524	1.03
	WDG-T4-0.99lg/SVC _{alpha=115} ⁰	1.9855	0.2829	0.99	23	–	–	–	1.8229	2.2014	2.7220	4.4513	0.1303	0.0922	79.21	84.42	6.84	97.49	0.6755	0.9777	1.03
	WDG-T4-0.99lg+SVC (–0.250)	2.1073	0.3002	0.99	07	115.44	–0.250	23	1.7197	2.1728	2.6933	4.3530	0.0842	0.0597	51.12	54.68	4.49	94.12	0.6549	0.9890	1.03
	WDG-T4-0.99lg+SVC (–0.500)	2.4334	0.3467	0.99	23	117.09	–0.500	6	1.3839	2.1607	2.4081	4.2957	0.0794	0.0523	68.89	54.50	4.41	92.70	0.6323	0.9996	1.03
	WDG-T4-0.99lg+SVC (+0.250)	1.7323	0.2468	0.99	16	112.25	+0.250	6	2.1750	2.2224	3.0812	4.4809	0.1340	0.0961	81.40	87.95	5.13	98.68	0.6873	0.9767	1.03
	WDG-T4-0.99lg+SVC (+0.500)	1.4686	0.2092	0.99	13	110.71	+0.500	29	2.3852	2.2350	3.2213	4.4665	0.1455	0.0999	84.13	88.21	5.38	98.80	0.6991	0.9660	1.03
REF	WODG_SVC	–	–	–	–	–	–	–	3.8369	2.3677	4.5086	4.4786	0.1769	0.1177	100	100	7.83	99.41	100	0.9494	1.03
	WDG-T4-0.99lg/SVC _{alpha=115} ⁰	1.6624	0.2368	0.99	27	–	–	–	2.1488	2.1250	3.0221	4.4337	0.0934	0.0666	52.81	56.59	5.48	97.23	0.7405	0.9771	1.03
	WDG-T4-0.99lg+SVC (–0.250)	1.8139	0.2584	0.99	26	115.44	–0.250	27	1.9971	2.1028	2.9000	4.4133	0.0908	0.0650	51.34	55.22	5.27	94.78	0.7181	0.9893	1.03
	WDG-T4-0.99lg+SVC (–0.500)	1.8562	0.2654	0.99	08	117.09	–0.500	30	1.9627	2.0972	2.8724	4.3903	0.0898	0.0619	50.76	52.57	4.91	91.02	0.6911	0.9914	1.03
	WDG-T4-0.99lg+SVC (+0.250)	1.5493	0.2207	0.99	26	112.25	+0.250	6	2.2595	2.1377	3.1105	4.4499	0.0971	0.0687	54.92	58.40	5.63	98.94	0.7506	0.9612	1.03
	WDG-T4-0.99lg+SVC (+0.500)	1.4505	0.2066	0.99	06	110.71	+0.500	6	2.3575	2.1497	3.1905	4.4582	0.1011	0.0711	57.18	60.39	5.77	98.99	0.7625	0.9504	1.03

as compared to the others. The values of weight factors of DPS performance indices are given in Table 9 on priority basis. In the present work, the above objective function is optimized by using GA.

These weights are intended to give the corresponding importance to each impact indices for the penetration of DG with load models and depend on the required analysis (e.g., planning, operation, etc.). The weighted normalized indices are used as the components of the objective function due to the fact that normally, the said indices get their weights by translating their impacts in terms of cost. The cost may either be determined rigorously or through an engineering judgment. Regardless of the fact that one of the particular objectives may get higher satisfaction on the cost of the others, it is desirable if the total cost decreases. However, if the harmonious solutions are desired, methods reported in Sheng et al. (2015), Kim et al. (2008), Akram et al. (2015), Gandomkar et al. (2005), Soroudi and Ehsan (2011), Ela et al. (2010), Wei et al. (2014), Sharma et al. (2003), Chris et al. (2015), Miranda et al. (1994), Akorede et al. (2011), Sebastian et al. (2015), Mohammadi et al. (2012), Hadi and Majid (2012), Kim et al. (2002), Akorede et al. (2011), Vinothkumar and Selvan (2011) and Singh et al. (2009) may be used. Table 10 shows the values for the weights used in present work, considering normal operation analysis and are similar to Al Abri et al. (2013), Sheng et al. (2015), Kim et al. (2008), Akram et al. (2015), Gandomkar et al. (2005), Soroudi and Ehsan (2011), Ela et al. (2010), Wei et al. (2014), Sharma et al. (2003), Chris et al. (2015), Miranda et al. (1994), Akorede et al. (2011), Sebastian et al. (2015), Mohammadi et al. (2012), Hadi and Majid (2012), Kim et al. (2002), Akorede et al. (2011), Vinothkumar and Selvan (2011) and Singh et al. (2009). However, these values may vary according to an engineer's concern. In this analysis PLI and QLI received first and second significant weight (0.40) and (0.30) respectively. The behavior of VDI received third significant weight of 0.10 due to its power quality impacts. The SCCI received fourth significant weight of (0.10) since it gives important information about the level of currents through the network regarding the maximum thermal capacity of conductors in distribution systems. The EIRI received fifth significant weight (0.10). This index shows the level of emission of GHG with different types of DGs and single FACTS controller like SVC.

The multi-objective function (defined in (34)) is minimized subjected to various operational constraints to satisfy the electrical requirements for distribution network. These constraints are discussed as follows:

- (i) *Power flow conservation limits*: The algebraic sum of all incoming and outgoing power including line losses over whole distribution network and power generated from DG and FACTS controller like SVC unit should be equal to zero in Eq. (36).

$$P_{SS}(i, V) = \sum_{x=2}^n P_{Demand}(x, V) + \sum_{n=1}^{N_L} P_{Loss}(V) - P_{WDG_SVC_FACTS_x} \quad (36)$$

where N_L is the number of lines, n is the number of buses in system, $P_{Demand}(x, V)$ is the power demand (MW), $P_{Loss}(V)$ is the power loss in system and $P_{WDG_SVC_FACTS_x}$ is the DG and FACTS controller like SVC power delivered to system.

- (ii) *Short circuit current capacity or distribution line thermal capacity limits*: Power flow through any distribution feeder must comply with the thermal capacity of the line as follows in (37):

$$S_{(x,y)} \leq S_{(x,y)max}. \quad (37)$$

- (iii) *Voltage deviation limits*: The voltage drop limits depend on the voltage regulation limits provided by the DISCO as follows in Eq. (38):

$$|V_1 - V_y| \leq \Delta V_{max}. \quad (38)$$

If voltage and MVA limits are satisfied in system buses for a particular size–location pair, accept that pair for next generation population, else reject the size–placement pair which does not satisfy voltage and MVA limits in the next generation. Obtain the size–placement pair for minimum MUOPIF. All possible generations are tested with operational constraints, the size and placement corresponding to minimum MUOPIF by the optimum size–placement pair of DG and single FACTS controller like SVC.

5. Simulation results and discussions

The effectiveness of the proposed methodology is tested on IEEE 37-bus distribution test system. The values of system and load data for IEEE 37-bus distribution test system are given in Table 10. The details of single-line diagram of IEEE 37-bus distribution system are shown in Fig. 6. The planning of different types of DGs (such as T_2 and T_4 are operating at different PFs such as 0.85, 0.90, 0.95, 0.99 leading and lagging respectively) and FACTS controller like SVC with DLMs (such as CON–INS–RES–COM–REF load models) by GA for minimum of total MVA intake of main substation viewpoint are as follows:

5.1. T_2 type DG (operating at 0.85 leading PF) and SVC

The results for planning of T_2 type DG (operating at 0.85 leading PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) and optimized by GA are featured in Table 11. The impact assessments of optimally placed T_2 type DG (operating at 0.85 leading PF) and SVC with DLMs, optimized by GA in DPSs are as follows:

Figs. 7–9, it is inferred that the DPS performance parameters and indices such as P_{intake} , Q_{intake} , S_{intake} , S_{system} , PL_{min} , QL_{min} , PLI, QLI, VDI, SCCI, EIRI and VP from the viewpoint of minimum total MVA intake of main substation and their respective T_2 type DG (operating at 0.85 leading PF) and SVC with DLMs such as CON–INS–RES–COM–REF load models are as follows:

- (i) *SVC behaves as generator mode*: The SVC behaves as generator mode means that RP delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to T_2 type DG (operating at 0.85 leading PF),
- (ii) *SVC behaves as resonance mode*: The SVC behaves as resonance mode means that RP neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are as same as T_2 type DG (operating at 0.85 leading PF),
- (iii) *SVC behaves as load mode*: The SVC behaves as load mode means RP absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to T_2 type DG (operating at 0.85 leading PF).

Thus, the DPS performance orders would be as follows: T_2 type DG (operating at 0.85 leading PF) and SVC (+0.500) means as load mode; $> T_2$ type DG (operating at 0.85 leading PF) and SVC (+0.250) means as load mode; $= T_2$ type DG (operating at 0.85 leading PF) and SVC (0.00) means as resonance mode; $< T_2$ type DG (operating at 0.85 leading PF) and SVC (–0.250) means as generator mode; $< T_2$ type DG (operating at 0.85 leading PF) and SVC (–0.500) means as generator mode.

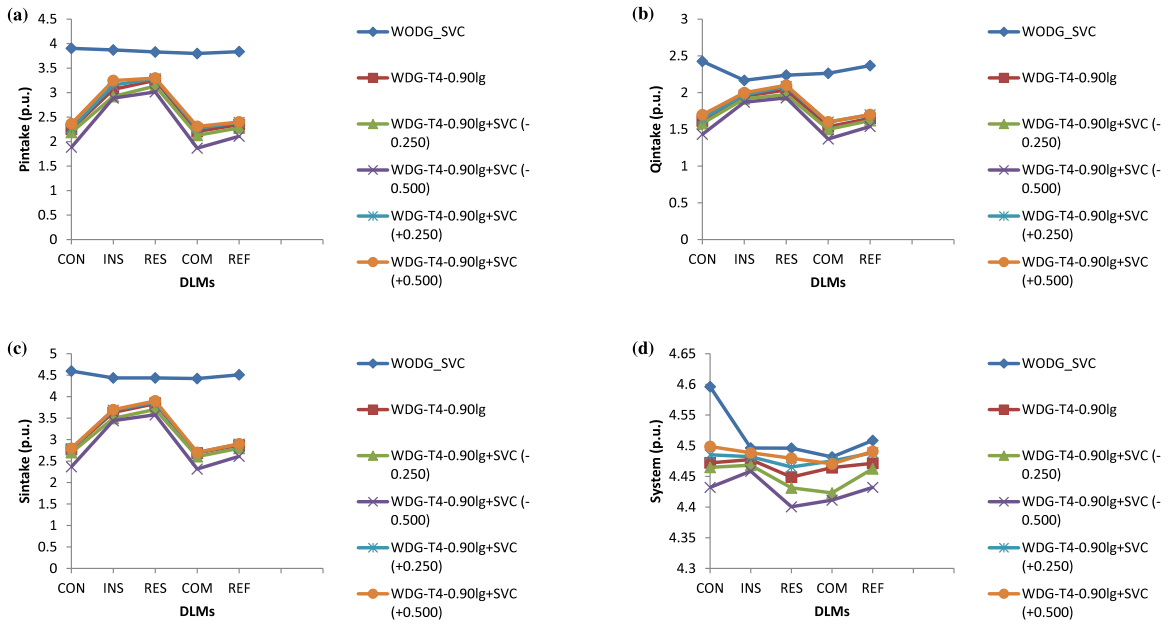


Fig. 22. Pertaining to DG (i.e. T_4 operating at 0.90 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{intake} , (b) Q_{intake} , (c) S_{intake} , and (d) S_{system} . *'lg' means lagging operating PFs of DGs; $T_4 = T_4$ type of DG.

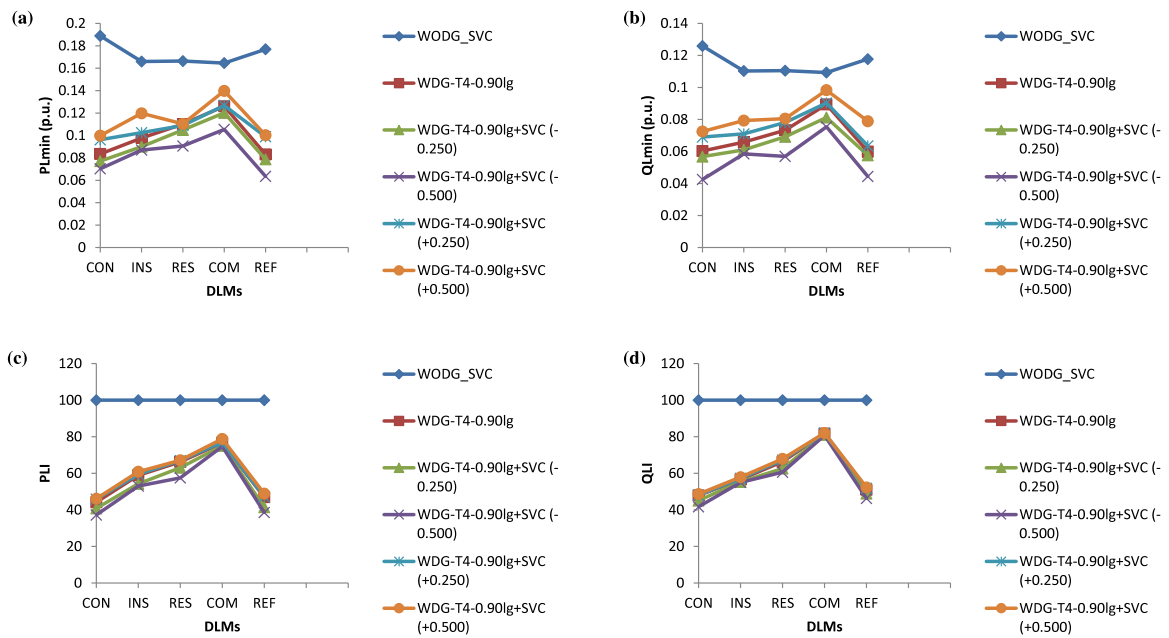


Fig. 23. Pertaining to DG (i.e. T_4 operating at 0.90 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{Lmin} , (b) Q_{Lmin} , (c) PLI , and (d) QLI . *'lg' means lagging operating PFs of DGs; $T_4 = T_4$ type of DG.

5.2. T_2 type DG (operating at 0.90 leading PF) and SVC

The results for planning of T_2 type DG (operating at 0.90 leading PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) and optimized by GA are featured in Table 12. The impact assessments of optimally placed T_2 type DG (operating at 0.90 leading PF) and SVC with DLMs, optimized by GA in DPSs are as follows:

Figs. 10–12, it is inferred that the PS performance parameters and indices such as P_{intake} , Q_{intake} , S_{intake} , S_{system} , PL_{min} , QL_{min} , PLI , QLI , VDI , $SCCI$, $EIRI$ and VP from the viewpoint of minimum total MVA intake of main substation and their respective T_2 type DG (operating at 0.90 leading PF) and SVC with DLMs such as CON–INS–RES–COM–REF load models are as follows:

- (i) *SVC behaves as generator mode:* The SVC behaves as generator mode means that RP delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to T_2 type DG (operating at 0.90 leading PF),
- (ii) *SVC behaves as resonance mode:* The SVC behaves as resonance mode means that RP neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are as same as T_2 type DG (operating at 0.90 leading PF),
- (iii) *SVC behaves as load mode:* The SVC behaves as load mode means that RP absorbed from the system bus hence the all PS performance parameters and indices are poor as compared to T_2 type DG (operating at 0.90 leading PF).

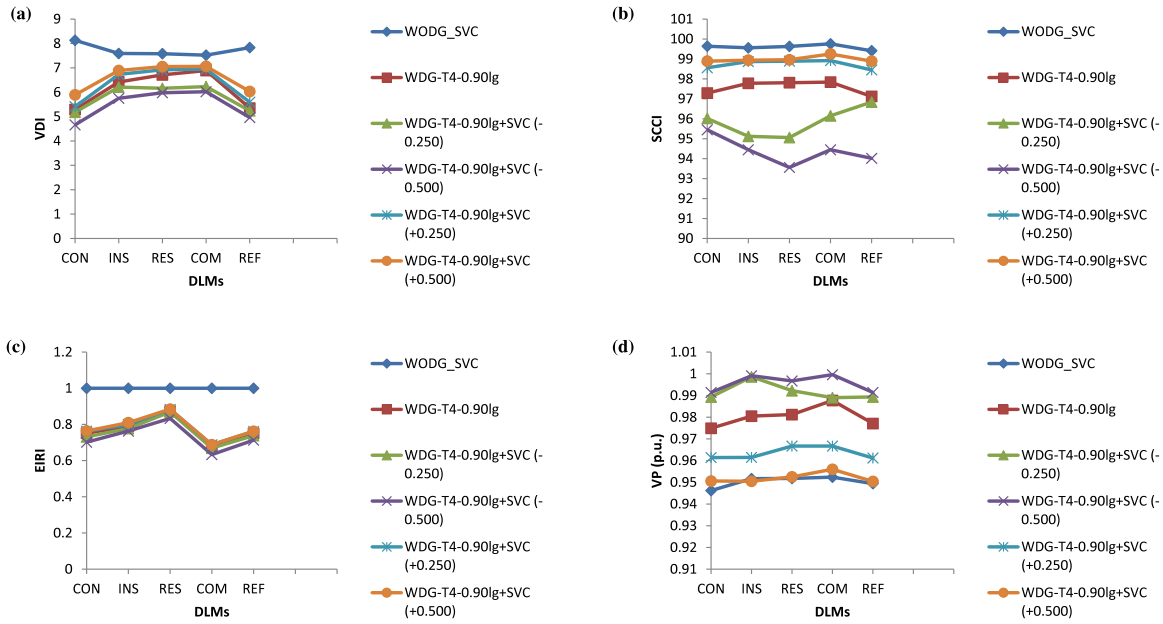


Fig. 24. Pertaining to DG (i.e. T_4 operating at 0.90 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) VDI, (b) SCCI, (c) EIRI, and (d) VP. *lg' means lagging operating PFs of DGs; $T_4 = T_4$ type of DG.

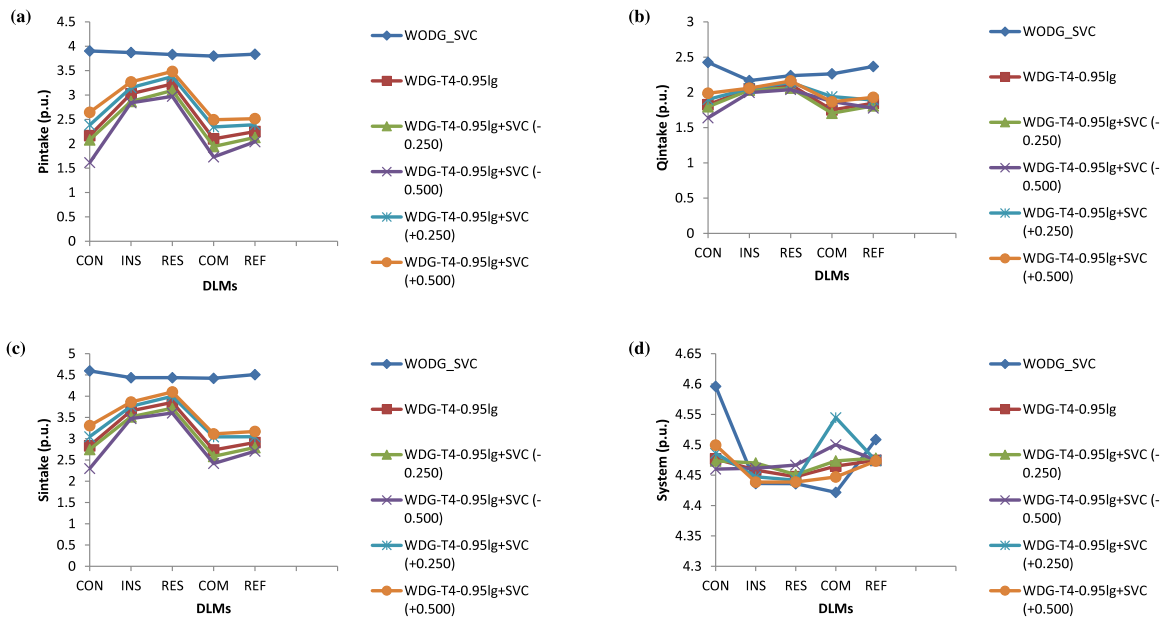


Fig. 25. Pertaining to DG (i.e. T_4 operating at 0.95 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{intake} , (b) Q_{intake} , (c) S_{intake} , and (d) S_{system} . *lg' means lagging operating PFs of DGs; $T_4 = T_4$ types of DGs.

Thus, the DPS performance orders would be as follows: T_2 type DG (operating at 0.90 leading PF) and SVC (+0.500) means as load mode; $> T_2$ type DG (operating at 0.90 leading PF) and SVC (+0.250) means as load mode; $> T_2$ type DG (operating at 0.90 leading PF); $= T_2$ type DG (operating at 0.90 leading PF) and SVC (0.00) means as resonance mode; $< T_2$ type DG (operating at 0.90 leading PF) and SVC (-0.250) means as generator mode; $< T_2$ type DG (operating at 0.90 leading PF) and SVC (-0.500) means as generator mode.

5.3. T_2 type DG (operating at 0.95 leading PF) and SVC

The results for planning of T_2 type DG (operating at 0.95 leading PF) and SVC with DLMs (such as CON–INS–RES–COM–REF

load models) and optimized by GA are featured in Table 13. The impact assessments of optimally placed T_2 type DG (operating at 0.95 leading PF) and SVC with DLMs, optimized by GA in DPSSs are as follows:

Figs. 13–15, it is inferred that the DPS performance parameters and indices such as P_{intake} , Q_{intake} , S_{intake} , S_{system} , PL_{min} , QL_{min} , PLI, QLI, VDI, SCCI, EIRI and VP from the viewpoint of minimum total MVA intake of main substation and their respective T_2 type DG (operating at 0.95 leading PF) and SVC with DLMs such as CON–INS–RES–COM–REF load models are as follows:

- (i) SVC behaves as generator mode: The SVC behaves as generator mode means that RP delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to T_2 type DG (operating at 0.95 leading PF),

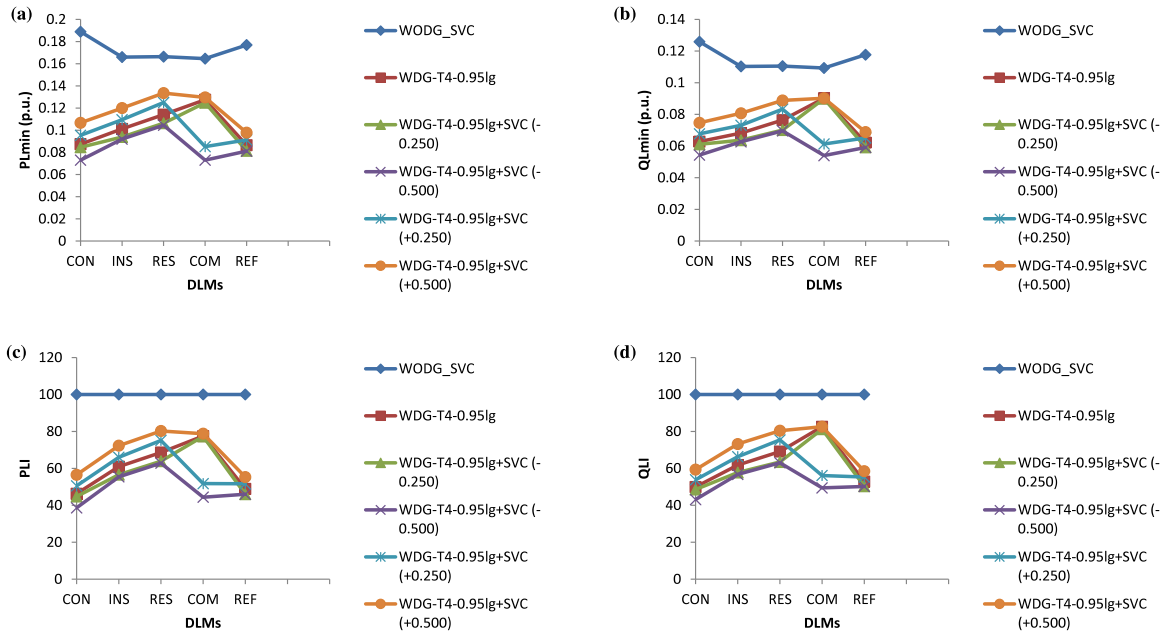


Fig. 26. Pertaining to DG (i.e. T_4 operating at 0.95 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{Lmin} , (b) Q_{Lmin} , (c) PLI, and (d) QLI. **lg** means lagging operating PFs of DGs; $T_4 = T_4$ type of DG.

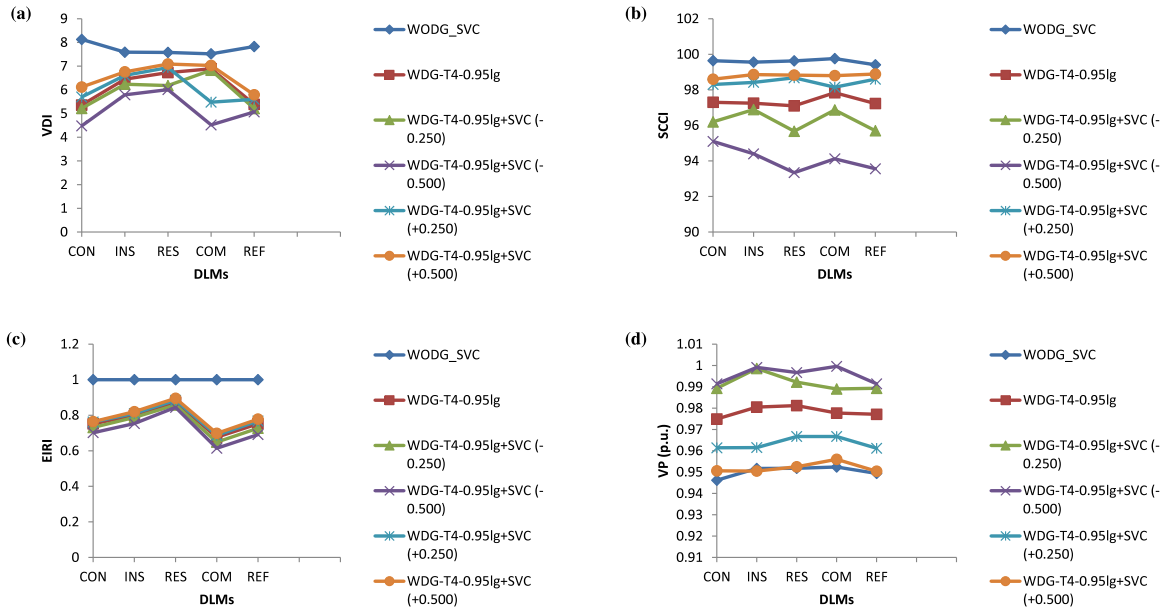


Fig. 27. Pertaining to DG (i.e. T_4 operating at 0.95 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) VDI, (b) SCCI, (c) EIRI, and (d) VP. **lg** means lagging operating PFs of DGs; $T_4 = T_4$ type of DG.

- (ii) *SVC behaves as resonance mode*: The SVC behaves as resonance mode means that RP neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are as same as T_2 type DG (operating at 0.95 leading PF),
- (iii) *SVC behaves as load mode*: The SVC behaves as load mode means that RP absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to T_2 type DG (operating at 0.95 leading PF).

Thus, the DPS performance orders would be as follows: T_2 type DG (operating at 0.95 leading PF) and SVC (+0.500) means as load mode; $> T_2$ type DG (operating at 0.95 leading PF) and SVC (+0.250) means as load mode; $> T_2$ type DG (operating at

0.95 leading PF); $= T_2$ type DG (operating at 0.95 leading PF) and SVC (0.00) means as resonance mode; $< T_2$ type DG (operating at 0.95 leading PF) and SVC (-0.250) means as generator mode; $< T_2$ type DG (operating at 0.95 leading PF) and SVC (-0.500) means as generator mode.

5.4. T_2 type DG (operating at 0.99 leading PF) and SVC

The results for planning of T_2 type DG (operating at 0.99 leading PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) and optimized by GA are featured in Table 14. The impact assessments of optimally placed T_2 type DG (operating at 0.99 leading PF) and SVC with DLMs, optimized by GA in DPSs are as follows:

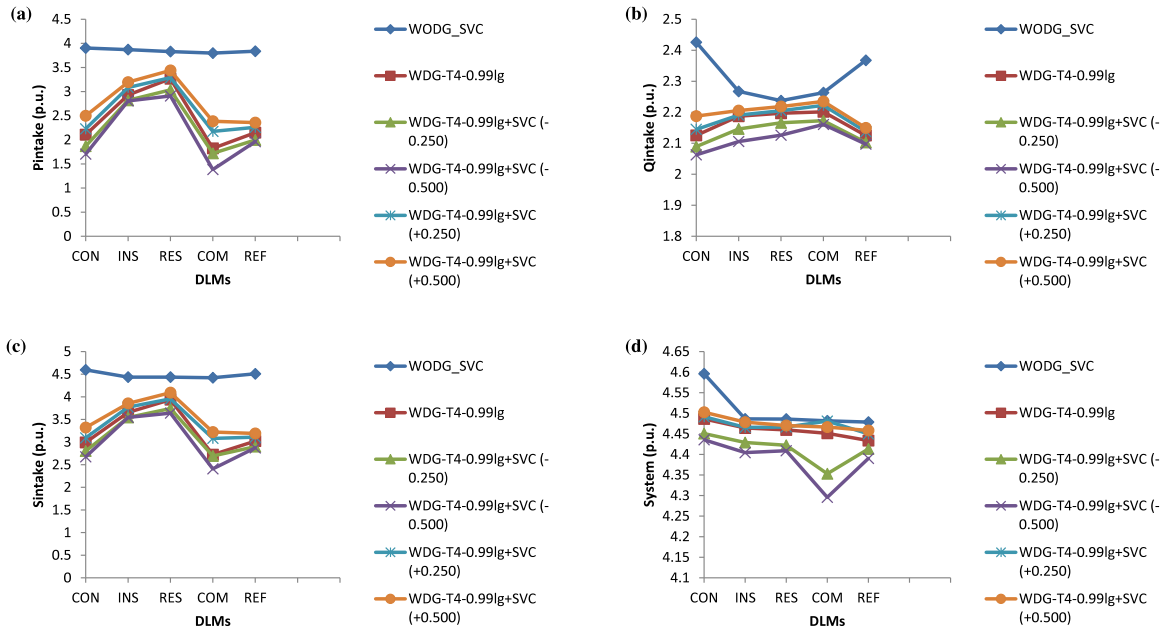


Fig. 28. Pertaining to DG (i.e. T_4 operating at 0.99 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{intake} , (b) Q_{intake} , (c) S_{intake} , and (d) S_{system} . *‘lg’ means lagging operating PFs of DGs; $T_4 = T_4$ type of DG.

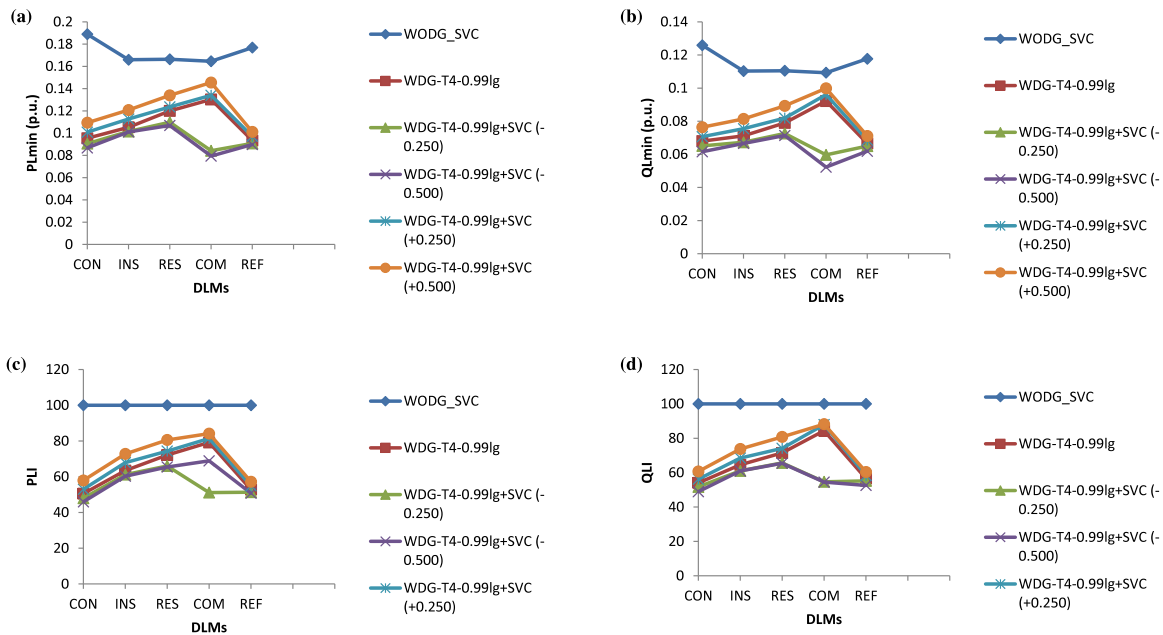


Fig. 29. Pertaining to DG (i.e. T_4 operating at 0.99 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF), profiles of (a) P_{Lmin} , (b) Q_{Lmin} , (c) PLI , and (d) QLI . *‘lg’ means lagging operating PFs of DGs; $T_4 = T_4$ type of DG.

Figs. 16–18, it is inferred that the DPS performance parameters and indices such as P_{intake} , Q_{intake} , S_{intake} , S_{system} , PL_{min} , QL_{min} , PLI , QLI , VDI , $SCCI$, $EIRI$ and VP from the viewpoint of minimum total MVA intake of main substation and their respective T_2 type DG (operating at 0.99 leading PF) and SVC with DLMs such as CON–INS–RES–COM–REF load models are as follows:

- (i) *SVC behaves as generator mode:* The SVC behaves as generator mode means that RP delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to T_2 type DG (operating at 0.99 leading PF),
- (ii) *SVC behaves as resonance mode:* The SVC behaves as resonance mode means that RP neither delivered nor absorbed

from the system bus, hence, all the DPS performance parameters and indices are as same as T_2 type DG (operating at 0.99 leading PF),

- (iii) *SVC behaves as load mode:* The SVC behaves as load mode means that RP absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to T_2 type DG (operating at 0.99 leading PF).

Thus, the DPS performance orders would be as follows: T_2 type DG (operating at 0.99 leading PF) and SVC (+0.500) means as load mode; $> T_2$ type DG (operating at 0.99 leading PF) and SVC (+0.250) means as load mode; $> T_2$ type DG (operating at 0.99 leading PF); $= T_2$ type DG (operating at 0.99 leading PF) and SVC (0.00) means as resonance mode; $< T_2$ type DG (operating at

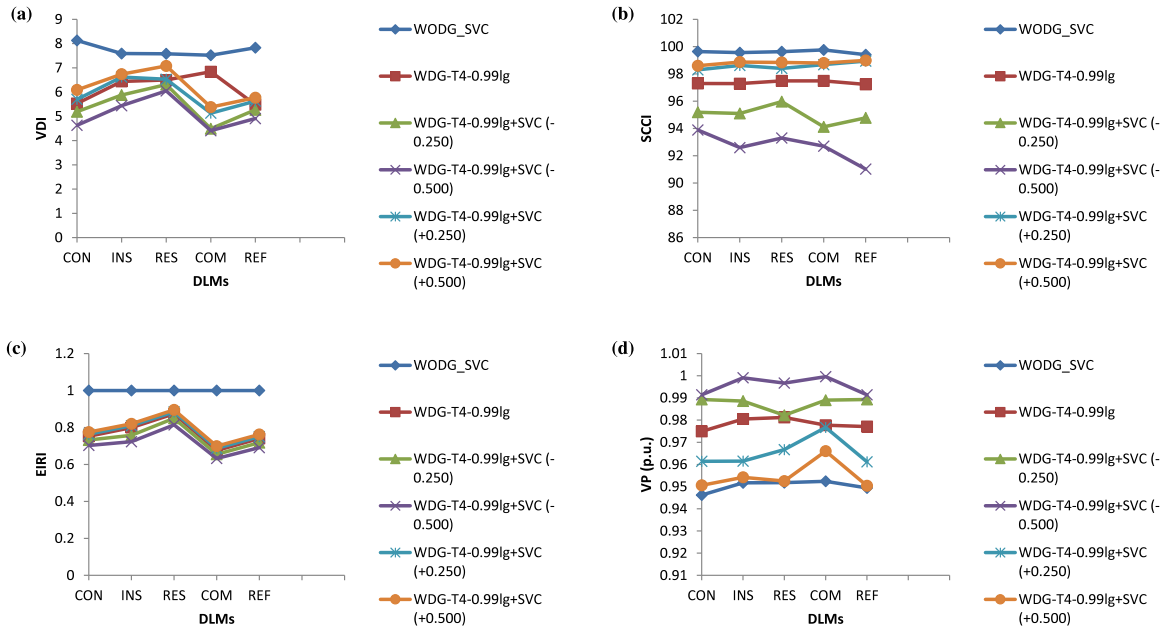


Fig. 30. Pertaining to DG (i.e. T_4 operating at 0.99 lagging PF) and SVC planned by GA with DLMs (such as CON–INS–RES–COM–REF) in DPSS, profiles of (a) VDI, (b) SCCI, (c) EIRI, and (d) VP. *‘lg’ means lagging operating PFs of DGs; $T_4 = T_4$ type of DG.

0.99 leading PF) and SVC (−0.250) means as generator mode; $<T_2$ type DG (operating at 0.99 leading PF) and SVC (−0.500) means as generator mode.

5.5. T_4 type DG (operating at 0.85 lagging PF) and SVC

The results for planning of T_4 type DG (operating at 0.85 lagging PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) and optimized by GA are featured in Table 15. The impact assessments of optimally placed T_4 type DG (operating at 0.85 lagging PF) and SVC with DLMs, optimized by GA in DPSS are as follows:

Figs. 19–21, it is inferred that the DPS performance parameters and indices such as P_{intake} , Q_{intake} , S_{intake} , S_{system} , PL_{min} , QL_{min} , PLI, QLI, VDI, SCCI, EIRI and VP from the viewpoint of minimum total MVA intake of main substation and their respective T_4 type DG (operating at 0.85 lagging PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) are as follows:

- (i) *SVC behaves as generator mode:* The SVC behaves as generator mode means that RP delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to T_4 type DG (operating at 0.85 lagging PF),
- (ii) *SVC behaves as resonance mode:* The SVC behaves as resonance mode means that RP neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are as same as T_4 type DG (operating at 0.85 lagging PF),
- (iii) *SVC behaves as load mode:* The SVC behaves as load mode means that RP absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to T_4 type DG (operating at 0.85 lagging PF).

Thus, the DPS performance orders would be as follows: T_4 type DG (operating at 0.85 lagging PF) and SVC (+0.500) means as load mode; $>T_4$ type DG (operating at 0.85 lagging PF) and SVC (+0.250) means as load mode; $>T_4$ type DG (operating at 0.85 lagging PF); $=T_4$ type DG (operating at 0.85 lagging PF) and SVC (0.00) means as resonance mode; $<T_4$ type DG (operating at 0.85 lagging PF) T_4 type DG (operating at 0.85 lagging PF) and SVC (−0.250) means as generator mode; $<T_4$ type DG (operating at 0.85 lagging PF) and SVC (−0.500) means as generator mode.

5.6. T_4 type DG (operating at 0.90 lagging PF) and SVC

The results for planning of T_4 type DG (operating at 0.90 lagging PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) and optimized by GA are featured in Table 16. The impact assessments of optimally placed T_4 type DG (operating at 0.90 lagging PF) and SVC with DLMs, optimized by GA in DPSS are as follows:

Figs. 22–24, it is inferred that the PS performance parameters and indices such as P_{intake} , Q_{intake} , S_{intake} , S_{system} , PL_{min} , QL_{min} , PLI, QLI, VDI, SCCI, EIRI and VP from the viewpoint of minimum total MVA intake of main substation and their respective T_4 type DG (operating at 0.90 lagging PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) are as follows:

- (i) *SVC behaves as generator mode:* The SVC behaves as generator mode means that RP delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to T_4 type DG (operating at 0.90 lagging PF),
- (ii) *SVC behaves as resonance mode:* The SVC behaves as resonance mode means that RP neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are as same as T_4 type DG (operating at 0.90 lagging PF),
- (iii) *SVC behaves as load mode:* The SVC behaves as load mode means that RP absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to T_4 type DG (operating at 0.90 lagging PF).

Thus, the DPS performance orders would be as follows: T_4 type DG (operating at 0.90 lagging PF) and SVC (+0.500) means as load mode; $>T_4$ type DG (operating at 0.90 lagging PF) and SVC (+0.250) means as load mode; $>T_4$ type DG (operating at 0.90 lagging PF); $=T_4$ type DG (operating at 0.90 lagging PF) and SVC (0.00) means as resonance mode; $<T_4$ type DG (operating at 0.90 lagging PF) T_4 type DG (operating at 0.90 lagging PF) and SVC (−0.250) means as generator mode; $<T_4$ type DG (operating at 0.90 lagging PF) and SVC (−0.500) means as generator mode.

5.7. T_4 type DG (operating at 0.95 lagging PF) and SVC

The results for planning of T_4 type DG (operating at 0.95 lagging PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) and optimized by GA are featured in Table 17. The impact assessments of optimally placed T_4 type DG (operating at 0.95 lagging PF) and SVC with DLMs, optimized by GA in DPSs are as follows:

Figs. 25–27, it is inferred that the DPS performance parameters and indices such as P_{intake} , Q_{intake} , S_{intake} , S_{system} , PL_{min} , QL_{min} , PLI , QLI , VDI , $SCCI$, $EIRI$ and VP from the viewpoint of minimum total MVA intake of main substation and their respective T_4 type DG (operating at 0.95 lagging PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) are as follows:

- (i) *SVC behaves as generator mode*: The SVC behaves as generator mode means that RP delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to T_4 type DG (operating at 0.95 lagging PF),
- (ii) *SVC behaves as resonance mode*: The SVC behaves as resonance mode means that RP neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are as same as T_4 type DG (operating at 0.95 lagging PF);
- (iii) *SVC behaves as load mode*: The SVC behaves as load mode means that RP absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to T_4 type DG (operating at 0.95 lagging PF).

Thus, the DPS performance orders would be as follows: T_4 type DG (operating at 0.95 lagging PF) and SVC (+0.500) means as load mode; $> T_4$ type DG (operating at 0.95 lagging PF) and SVC (+0.250) means as load mode; $> T_4$ type DG (operating at 0.95 lagging PF); $= T_4$ type DG (operating at 0.95 lagging PF) and SVC (0.00) means as resonance mode; $< T_4$ type DG (operating at 0.95 lagging PF) T_4 type DG (operating at 0.95 lagging PF) and SVC (–0.250) means as generator mode; $< T_4$ type DG (operating at 0.95 lagging PF) and SVC (–0.500) means as generator mode.

5.8. T_4 type DG (operating at 0.99 lagging PF) and SVC

The results for planning of T_4 type DG (operating at 0.99 lagging PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) and optimized by GA are featured in Table 18. The impact assessments of optimally placed T_4 type DG (operating at 0.99 lagging PF) and SVC with DLMs, optimized by GA in DPSs are as follows:

Figs. 28–30, it is inferred that the DPS performance parameters and indices such as P_{intake} , Q_{intake} , S_{intake} , S_{system} , PL_{min} , QL_{min} , PLI , QLI , VDI , $SCCI$, $EIRI$ and VP from the viewpoint of minimum total MVA intake of main substation viewpoint and their respective T_4 type DG (operating at 0.99 lagging PF) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) are as follows:

- (i) *SVC behaves as generator mode*: The SVC behaves as generator mode means that RP delivered to the system bus, hence, all the DPS performance parameters and indices are better as compared to T_4 type DG (operating at 0.99 lagging PF),
- (ii) *SVC behaves as resonance mode*: The SVC behaves as resonance mode means that RP neither delivered nor absorbed from the system bus, hence, all the DPS performance parameters and indices are as same as T_4 type DG (operating at 0.99 lagging PF),
- (iii) *SVC behaves as load mode*: The SVC behaves as load mode means that RP absorbed from the system bus, hence, all the DPS performance parameters and indices are poor as compared to T_4 type DG (operating at 0.99 lagging PF).

Thus, the DPS performance orders would be as follows: T_4 type DG (operating at 0.99 lagging PF) and SVC (+0.500) means as load mode; $> T_4$ type DG (operating at 0.99 lagging PF) and SVC (+0.250) means as load mode; $> T_4$ type DG (operating at 0.99 lagging PF); $= T_4$ type DG (operating at 0.99 lagging PF) and SVC (0.00) means as resonance mode; $< T_4$ type DG (operating at 0.99 lagging PF) T_4 type DG (operating at 0.99 lagging PF) and SVC (–0.250) means as generator mode; $< T_4$ type DG (operating at 0.99 lagging PF) and SVC (–0.500) means as generator mode.

5.9. Comparisons of results

Tables 11–18, shows the comparison of results of impact assessment of optimally placed different types of DGs (such as T_2 and T_4 are operating at different PFs such as 0.85, 0.90, 0.95, 0.99 leading and lagging respectively) and SVC with DLMs (such as CON–INS–RES–COM–REF load models) optimized by GA. Finally, it is concluded that T_2 type DG and SVC gives better DPS performance indices as compared to T_4 type DG and SVC with DLMs.

6. Conclusions and future scope of research work

6.1. Conclusions

This paper presents the impact assessment of optimally placed different types of DGs (such as T_2 and T_4 i.e. operating at different power factors such as 0.85, 0.90, 0.95 and 0.99 leading and lagging, respectively) and FACTS controllers like SVC with DLMs by using GA in PSs from minimum total MVA intake of main substation viewpoint. This paper focuses on reduction of the real power loss of system. The effectiveness of the proposed methodology is tested on IEEE 37-bus distribution test system. It is observed that the different types of DGs (such as T_2 and T_4 i.e. operating at different power factors such as 0.85, 0.90, 0.95 and 0.99 leading and lagging respectively) and FACTS controllers like SVC with DLMs show different behaviors for DPS performance indices such as PLI , QLI , VDI , $SCCI$, and $EIRI$. Finally, it is concluded that T_2 type DG gives better PS performance indices as compared to T_4 types DG and FACTS controllers like SVC with DLMs.

This paper discusses the important topic of integration of renewable energy sources such as DGs and FACTS controllers in the electricity grid while taking into account different DPS performance indicators.

6.2. Recommendations for scope of future research work

The following recommendations for the scope of research work in this direction may be carried out in future.

- (i) Application of Artificial Intelligence (AI) techniques for optimal location and properly coordinated control of DGs and Flexible Alternating Current Transmission Systems (FACTS) controllers such as Static Compensator (STATCOM) and Distributed-STATCOM (D-STATCOM) in DPSs with static load models only for better DPS performance indices.
- (ii) Application of AI techniques for optimal location and properly coordinated control of DGs and FACTS controllers such as STATCOM and D-STATCOM in DPSs with static as well as realistic load models for better PS performance indices.
- (iii) Application of hybrid AI techniques for optimal location and properly coordinated control of DGs and FACTS controllers such as STATCOM and D-STATCOM in DPSs with static load models only for better PS performance indices.

- (iv) Application of hybrid AI techniques for optimal location and properly coordinated control of DGs and FACTS controllers such as STATCOM and D-STATCOM in DPSs with static as well as realistic load models for better PS performance indices.
- (v) Application of AI techniques for optimal location and properly coordinated control of DGs and FACTS controllers such as STATCOM and D-STATCOM in DPSs with static load models with seasonal criterion only for better PS performance indices.
- (vi) Application of AI techniques for optimal location and properly coordinated control of DGs and FACTS controllers such as STATCOM and D-STATCOM in DPSs with static load models with seasonal criterion as well as realistic load models for better PS performance indices.
- (vii) Application of hybrid AI techniques for optimal location and properly coordinated control of DGs and FACTS controllers such as STATCOM and D-STATCOM in DPSs with static load models with seasonal criterion only for better PS performance indices.
- (viii) Application of hybrid AI techniques for optimal location and properly coordinated control of DGs and FACTS controllers such as STATCOM and D-STATCOM in DPSs with static load models with seasonal criterion as well as realistic load models for better PS performance indices.
- (ix) It is recommended for the scope of future work for practitioners working on the implementation of renewable (DG + FACTS controllers) and building of future electricity grids and also includes the different PS performance indicators for better social welfare, reduced in the environmental pollutants emission, improved the technical issues, reduced the economical burden, and betters the security viewpoints.
- (x) It is also recommended for the scope of future work for practitioners working on the implementation of renewable and building of future electricity grids and also includes the different PS performance indicators for optimal placement and properly coordinated control of multiple DG and FACTS controllers in DPSs.
- (xi) The classification of different types of DGs (such as T_1 , T_2 , T_3 and T_4) and FACTS controllers on the basis of real and reactive power delivered/absorbed to system. So that different types of DGs and FACTS controllers are useful as per requirement of load demands. Finally it is also important for practitioners working on the implementation of renewable and building of future electricity grids.

References

Akorede, M.F., Hizam, H., Aris, I., Kadir, M.Z.A.A., 2011. Effective method for optimal allocation of DG units in meshed electric power systems. *IET Gener. Transm. Distrib.* 5 (2), 276–287.

- Akram, E., Mohammed, E., Mohammed, E., Zhe, C., 2015. A fuzzy-multiagent self-healing scheme for a distribution system with distributed generations. *IEEE Trans. Power Syst.* 30 (5), 2612–2622.
- Al Abri, R.S., El-Saadany, E.F., Atwa, Y.M., 2013. Optimal placement and sizing method to improve the voltage stability margin in a distribution system using distributed generation. *IEEE Trans. Power Syst.* 28 (1), 326–334.
- Aziz, T., Hossain, M.J., Saha, T.K., Mithulananthan, N., 2013. VAR planning with tuning of STATCOM in a DG integrated industrial system. *IEEE Trans. Power Deliv.* 28 (2), 875–885.
- Chiradeja, P., Ramakumar, R., 2004. An approach to quantify the technical benefits of DG. *IEEE Trans. Energy Convers.* 19 (4), 764–773.
- Chris, J.D., Alex Hernandez, O., Simon, R.B., David, M., David, R., 2015. Defining and evaluating the capacity value of distributed generation. *IEEE Trans. Power Syst.* 30 (5), 2329–2337.
- Claudio, A.C., Faur, Z.T., 1999. Analysis of SVC and TCSC controllers in voltage collapse. *IEEE Trans. Power Syst.* 14 (1), 158–165.
- Ela, A.A.A.E., Allam, S.M., Shatla, M.M., 2010. Maximal optimal benefits of DG using GAs. *Electr. Power Syst. Res.* 80 (7), 869–877.
- Gandomkar, M., Vakilian, M., Ehsan, M., 2005. A genetic-based tabu search algorithm for optimal DG allocation in distribution networks. *Electr. Power Compon. Syst.* 33 (12), 1351–1362.
- Hadi, H., Majid, G., 2012. A straightforward approach to minimizing unsupplied energy and power loss through DG placement and evaluating power quality in relation to load variations over time. *Int. J. Electr. Power Energy Syst.* 35 (1), 393–396.
- Hong, Y.Y., Ho, S.Y., 2005. Determination of network configuration considering multiobjective in distribution systems using genetic algorithms. *IEEE Trans. Power Syst.* 20 (2), 1062–1069.
- Kim, K.H., Lee, Y.J., Rhee, S.B., Lee, S.K., You, S.K., 2002. Dispersed generator placement using fuzzy-GA in distribution systems. In: *Proc. IEEE Power Eng. Soc. Summer Meeting*, Vol. 23, pp. 1148–1153.
- Kim, K.H., Song, K.B., Joo, S.K., Lee, Y.J., Kim, J.O., 2008. Multi-objective DG placement using fuzzy goal programming with GA. *Eur. Trans. Electr. Power* 18 (3), 217–230.
- Krishnan, M., 2015. Intelligent energy control center for distributed generators using multi-agent system. *IEEE Trans. Power Syst.* 30 (5), 2442–2449.
- Miranda, V., Ranito, J.V., Proenca, L.M., 1994. Genetic algorithms in optimal multistage distribution network planning. *IEEE Trans. Power Syst.* 9 (4), 1927–1933.
- Mohammadi, M., Hosseinian, S.H., Gharehpetian, G.B., 2012. GA-based optimal sizing of microgrid and DG units under pool and hybrid electricity markets. *Int. J. Electr. Power Energy Syst.* 35 (1), 483–492.
- Ochoa, L.F., Padilha-Feltrin, A., Harrison, G.P., 2006. Evaluating DG impacts with a multi-objective index. *IEEE Trans. Power Deliv.* 21 (3), 1452–1458.
- Sebastian, B., Albert, C., Bernhard, S., 2015. Capacity of low-voltage grids for distributed generation: Classification by means of stochastic simulations. *IEEE Trans. Power Syst.* 30 (2), 689–700.
- Sharma, N.K., Ghosh, A., Verma, R.K., 2003. A novel placement strategy for FACTS controllers. *IEEE Trans. Power Deliv.* 18 (3), 982–987.
- Sheng, W., Liu, K.Y., Liu, Y., Meng, X., Li, Y., 2015. Optimal placement and sizing of DG via an improved nondominated sorting genetic algorithm-II. *IEEE Trans. Power Deliv.* 30 (2), 569–578.
- Singh, D., Singh, D., Verma, K.S., 2009. Multi-objective optimization for DG planning with load models. *IEEE Trans. Power Syst.* 24 (1), 427–436.
- Soroudi, A., Ehsan, M., 2011. Efficient immune-GA method for DNOs in sizing and placement of DG units. *Eur. Trans. Electr. Power* 21 (3), 1361–1375.
- Vinothkumar, K., Selvan, M.P., 2011. Fuzzy embedded GA method for DGs planning. *Electr. Power Compon. Syst.* 39 (4), 346–366.
- Wei, Y., Jiang, L., Wen, J., Wu, Q.H., Cheng, S., 2014. Wide-area damping controller of FACTS devices for inter-area oscillations considering communication time delays. *IEEE Trans. Power Syst.* 29 (1), 318–329.