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On the representation of demand-side management in power system models

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Abstract: Demand-side management (DSM) merits increased attention by power system modelers. We argue that numerical models should incorporate DSM constraints in a complete and consistent way. Otherwise, flawed DSM patterns and distorted conclusions on the system benefits of demand-side management are inevitable. Building on a model formulation put forward by Göransson et al. (2014), we first suggest an improvement that resolves the problem of undue DSM recovery. We further introduce an alternative model that increases the real-world applicability of demand-side management modeling. Our formulation, which is both concise and linear, could readily be included in a wide range of numerical models.

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1 Introduction

The application of demand-side management (DSM) in power systems recently gains increasing attention in many countries as it provides a means of accommodating growing power generation from fluctuating renewable sources, and may help to address carbon emissions constraints, network restrictions, and concerns about capacity adequacy (Strbac 2008, Aghaei and Alizadeh 2013, Bergaentzlé et al. 2014). Moreover, the demand side is viewed as a potentially relevant source for the provision of reserves (Koliou et al. 2014, Falsafi et al. 2014). There is no common definition of demand-side management, and many authors differentiate only vaguely between DSM, demand response, and (temporarily) increased energy efficiency (e.g., Miara et al. 2014). DSM may refer to increased responsiveness to real-time prices (cf. Borenstein 2005, Allcott 2012), load shifting between periods, temporary load shedding, or both of the latter (e.g., Paulus and Borggrefe 2011, Keane et al. 2011). DSM may be realized in industrial, commercial or domestic applications. In the case of load shifting, which we focus on in the following, overall power demand does not change over the whole time frame considered; yet some fraction of load may be moved between single hours, for example from periods with high power prices or binding network constraints to hours with lower prices or lower congestion. Torriti et al. (2010) and Bradley et al. (2013) review some practical experiences as well as costs and benefits of DSM programs in Europe. There are substantial potentials for DSM applications in different sectors and countries (Stadler and Bukvić-Schäfer 2003, EPRI 2009, Gils 2014).

Many power system models incorporate some form of DSM representation. Yet given the growing importance of DSM, surprisingly little attention is drawn to the intricacies of load shifting. A proper representation of DSM requires not only a maximum power restriction on hourly load shifting, but also consistent time-related constraints which ensure that load changes in one direction are adequately evened out by changes in the opposite direction in due time. An incomplete representation of these constraints may result in exaggerated levels of DSM utilization and, accordingly, flawed assessments on the capabilities and benefits of DSM in power systems.

To our knowledge, previous model analyses largely do not incorporate these restrictions in a coherent way. For example, Schroeder (2011) focuses on DSM modeling, but merely includes an hourly power restriction and an overall energy balance equation for the whole time frame considered. Pina et al. (2012) analyze the impact of DSM on renewable penetration in an island setting with the TIMES model, but do not document DSM restrictions.[3] Paulus and Borggrefe (2011) differentiate between load shedding and load shifting and also include the provision of reserves by DSM. Load shifting is modeled similar to power storage with an additional energy balance equation for certain time intervals.[4] Load shedding processes are constrained by an overall seasonal energy restriction. In a related setting, Richter (2011) considers restrictions with regard to both hourly load shifts and overall energy shifted in specific subsets of the whole time frame considered, but is rather vague about how these subsets are implemented. Keane et al. (2011) draw on a comparable

[3] We infer from the TIMES documentation (Loulou et al. 2005) published by the International Energy Agency that the model includes no more than an hourly power restriction and an overall energy balance constraint on DSM.

[4] Paulus and Borggrefe (2011) do not present an analytical representation of their DSM formulation. This can only be found in an older conference paper version. The details of the formulation still remain somewhat opaque, in particularly the specifics of the intervals considered, as well as the interplay of restrictions related to storage size and shifting time. It further remains questionable if DSM can be modeled in a setting with single type days in a meaningful way.

framework. Hayes et al. (2014) as well as Falsafi et al. (2014) merely consider hourly power constraints and do not include any time-related restrictions on load shifting.

Another strand of the literature covers DSM potentials related to particular thermal applications. In these specific cases, the analytical formulation is less challenging, as electric load shifts can be represented as thermal storage. For example, Hedegaard and Balyk (2013) model flexible operation of heat pumps combined with various types of thermal storage. Fehrenbach et al. (2014) extend the TIMES model to include thermal DSM, with a focus on the interaction of cogeneration, heat pumps and thermal storage.

Many other papers dealing with demand response, such as Choi and Thomas (2012) or Allcott (2012) just rely on price-sensitivity of demand and do not include explicit load shifting at all. In contrast, De Jonghe et al. (2014) model demand response in a unit commitment framework by not only including hourly own-price elasticities, but also cross-price elasticities to account for load shifts between hours. Yet this approach still does not ensure a zero net balance of load shifts in a given period of time.

In the following, we specifically comment on a recent article by Göransson et al. (2014). In contrast to many other analyses, Göransson et al. present a concise yet comprehensive DSM formulation. While this deserves merit, we identify potential improvements. In addition, we propose an alternative formulation that further advances both the flexibility and the realism of DSM representations in power system models. Our formulation could readily be implemented in a wide range of applications. Importantly, we do not aim to give a detailed account on the operational constraints of specific DSM processes like, for example, Ramanathan and Vittal (2008). Rather, we are interested in a generic representation of DSM from a power system modeler's perspective.

2 Improving the DSM formulation presented by Göransson et al.

Göransson et al. (2014) introduce a concise, linear, and largely convincing method of including DSM in a power system model. Yet there are two drawbacks. First, their formulation allows for undue recovery of load shifts which may violate the time-related shifting constraint. Second, load shifts always start with a delay of demand, i.e., with a downward adjustment of load. In this section, we focus on the first drawback, while section 3 addresses the second one.

Göransson et al. (2014) represent DSM as follows:[5]

$$dh_t \leq \sum_{l=0}^{L-1} dd_{t-l} \qquad \forall t \qquad (1)$$

$$dh_t \leq \sum_{l=1}^{L} ds_{t+l} \qquad \forall t \qquad (2)$$

$$dh_t = dh_{t-1} + dd_t - ds_t \qquad \forall t \qquad (3)$$

Assuming a delay time L of the DSM process, (1) constrains cumulative demand put on hold dh_t at time t by the sum of hourly delayed demand dd_t over previous $L-1$ periods, including the current

[5] Göransson et al. also include a spatial resolution with a regional index i, which we exclude for the sake of brevity.

hour. Likewise, (2) constrains dh_t by the sum of hourly demand served ds_t over the next L hours. Equation (3) is the balance of cumulative demand on hold, given its previous period level and the net of demand delayed and demand served.[6] Furthermore, we infer restrictions on maximum hourly load shifting (4 and 5) from what Göransson et al. provide in written form (section 2.2.4, page 865). These are not explicitly stated in the paper.

$$dd_t \leq C^{dd} \qquad \forall t \qquad (4)$$

$$ds_t \leq C^{ds} \qquad \forall t \qquad (5)$$

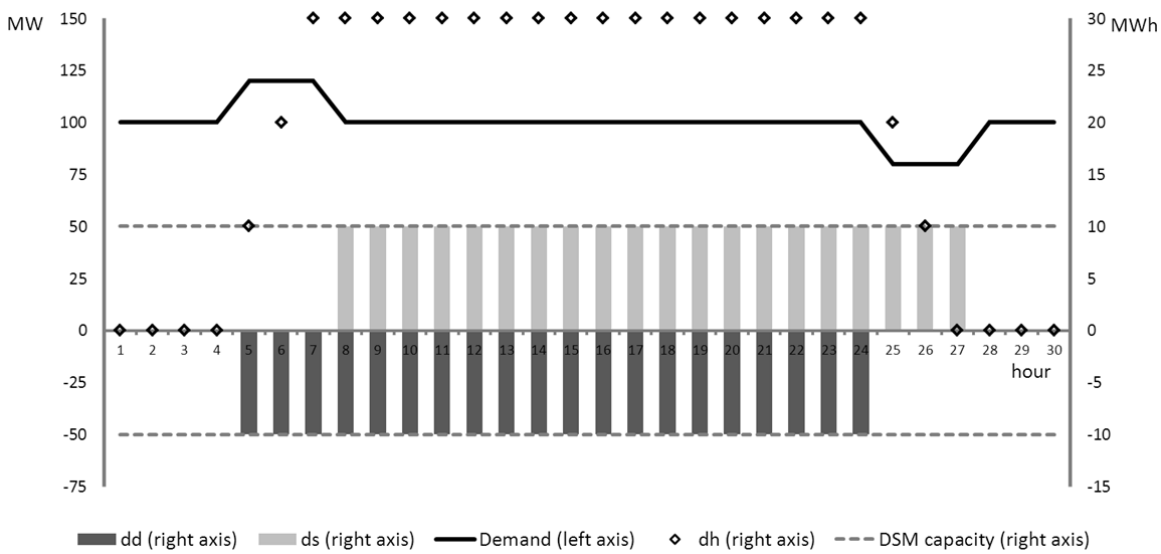
Equations (4-5) ensure that hourly delayed demand does not exceed an hourly threshold capacity C^{dd}, and hourly demand served may not exceed its threshold capacity C^{ds}. Although not stated by the authors, we further infer that dh_t, dd_t and ds_t are all positive variables. Otherwise, excessive levels of demand on hold would be possible.

Combining (1-5) results in largely compelling patterns of DSM utilization. Yet the formulation allows single DSM units to shift demand both up *and* down within the same period at full capacity rating. While this may be considered as a small distortion on first sight, it allows for undue DSM recovery, and may ultimately result in a serious overestimation of longer-term load shifts. This is exemplified by the following numerical example, which we carry out with a stylized dispatch model that minimizes variable costs.

Consider a case with only two generation technologies, one with low marginal costs (100 MW) and one with high costs (20 MW). Demand is flat at 100 MW in most hours, but there is a peak situation with 120 MW and an off-peak situation with 80 MW. A DSM technology is present with a delay time L of 3 hours, hourly load shift capacities $C^{dd} = C^{ds}$ of 10 MWh, and negligible marginal costs. The formulation presented by Göransson et al. leads to the the DSM pattern shown in Figure 1. After the first three hours of delayed demand, demand on hold stays at the maximum possible level of 30 MWh for many hours. This is made possible by repeatedly dispatching both dd_t and ds_t at full capacity in each hour. We interpret this as an instance of "undue recovery", as it means that demand served is instantaneously compensated by new demand delayed within the same DSM process. For clarification, let us adopt a "granular" interpretation of the DSM potential, in which the overall capacity consists of a large number of small single units that can either increase their load at full capacity rating *or* decrease it, or are inactive in any given hour. Then, the pattern in Figure 1 implies that the *same* granular units are dispatched upward and downward simultaneously. The formulation thus effectively circumvents the delay time restriction.

[6] dh_t, dd_t and ds_t may all be measured in MWh, or MWh per hour, respectively. In a model with hourly time steps, MWh and MW are essentially equivalent.

Figure 1: A case of undue recovery



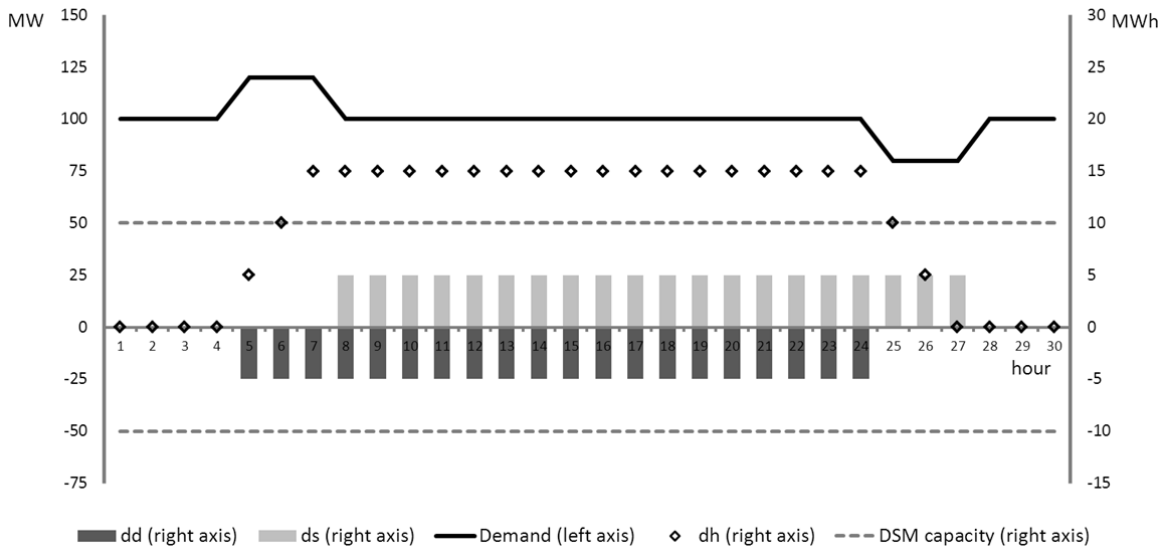
As a remedy of this problem, we propose introducing an additional constraint on maximum hourly load shifting. We include an additional equation (6) which implies that the same DSM capacity cannot shift demand up and down at full capacity at the same time. Without loss of generality, suppose that $C^{dd} \geq C^{ds}$.[7] Then dd_t has not only to be smaller than C^{dd}, as required by (4), but is further constrained by same-period upshifts of demand ds_t according to (6). At the same time, (6) constrains ds_t further than (5) if dd_t is larger than the difference between C^{dd} and C^{ds}. From a granular DSM perspective, (6) ensures that each granular DSM unit can only be shifted once, either up or down, in each period. Note that for $C^{dd} \geq C^{ds}$, (6) implies equation (4), which therefore does not have to be explicitly included.

$$dd_t + ds_t \leq \max\{C^{dd}, C^{ds}\} \qquad \forall t \qquad (6)$$

We return to our stylized example, this time including equation (6). Figure 2 shows that the DSM capacity is no longer fully utilized in both directions at the same time. Rather, only half of the capacity (5 MWh) is used in any period, such that each portion of demand delayed can be released by a corresponding level of demand served in due time. Demand on hold accordingly remains at 15 MWh, which is only half of the level that would be possible during shorter load shifts, and also only half of the level of the flawed model. Accordingly, the drawback of the model proposed by Göransson et al., that is an overestimation of longer-term load shifts, may be effectively cured by the small adjustment proposed here.

[7] A similar reasoning applies if $C^{dd} \leq C^{ds}$.

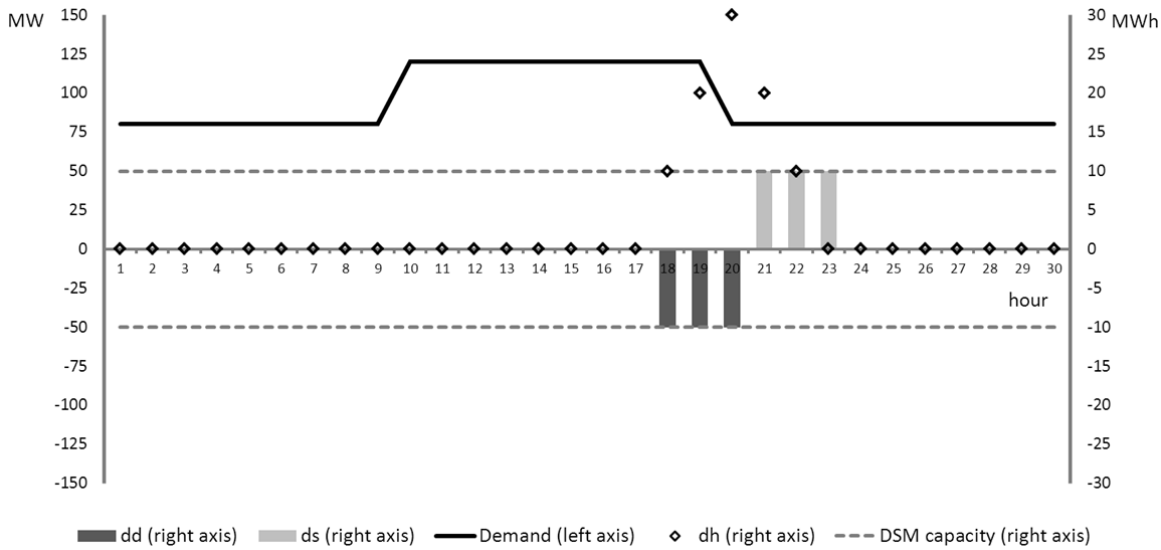
Figure 2: A case without undue recovery



3 Benefits of an alternative DSM formulation

A further shortcoming of specifying a DSM model according to (1-5) is related to the specific temporal structure imposed on load shifts. More precisely, loads first have to be put on hold, i.e., shifted down, and afterwards have to be served. It is, however, not possible to start the DSM process with an upward load shift. This may not adequately represent the real-world capabilities of various DSM processes which are in fact able to increase power consumption when in baseline operational mode, such as, for example, cold storage houses. We illustrate this problem by drawing on another stylized numerical example. Here, we assume the same generation and DSM capacities as above, but a temporary load increase from 80 to 120 MW. Figure 3 shows that demand is put on hold at the end of the temporary load distortion. In contrast, an inversed load shift does not occur at the beginning of the distortion, as negative load shifts in, say, period 10 cannot be served by positive shifts in previous periods.

Figure 3: Specific temporal structure of load shifts according to Göransson et al. (2014)



While sticking to the DSM model provided by equations (1-6), this problem could in general be solved by including a corresponding second set of parameters, variables, and equations which start with positive demand shifts. Yet this approach would entail an unnecessary increase in the number of variables and equations. It would also require assigning real-world DSM potentials, which may in fact be able to shift loads in both directions in the first place, partly to both stylized DSM representations. We thus propose a more parsimonious model which solves these problems.

We introduce positive variables DSM_t^{up} and $DSM_{t,tt}^{do}$ which represent hourly load shifts in upward or downward direction. These resemble ds_t and dd_t, with the exception that $DSM_{t,tt}^{do}$ has two time-related indices. $DSM_{t,tt}^{do}$ represents downward load shifts effective in hour tt to compensate for upward shifts in hour t. In doing so, we directly tag downward load shifts to the respective upward shift. Equation (7) ensures that every upward load shift is compensated by according downward shifts in due time, which may take place either before the upward load shift, after it, or both. Equations (8-9) restrict maximum hourly upward and downward shifts to installed capacites C^{up} and C^{do}, just like (4-5) in the above formulation. Note that only one of these two equations is relevant, depending on which restriction is tighter; the other constraint is implicitly rendered by (10). If, for instance, $C^{do} \geq C^{up}$, (9) contains redundant information and can be ignored. Equation (10) is the respective counterpart to (6). Note that this formulation does neither require a variable for the overall energy being shifted at a certain point in time, such as dh_t, nor a respective restriction corresponding to (3).

$$DSM_t^{up} = \sum_{tt=t-L}^{t+L} DSM_{t,tt}^{do} \qquad \forall t \qquad (7)$$

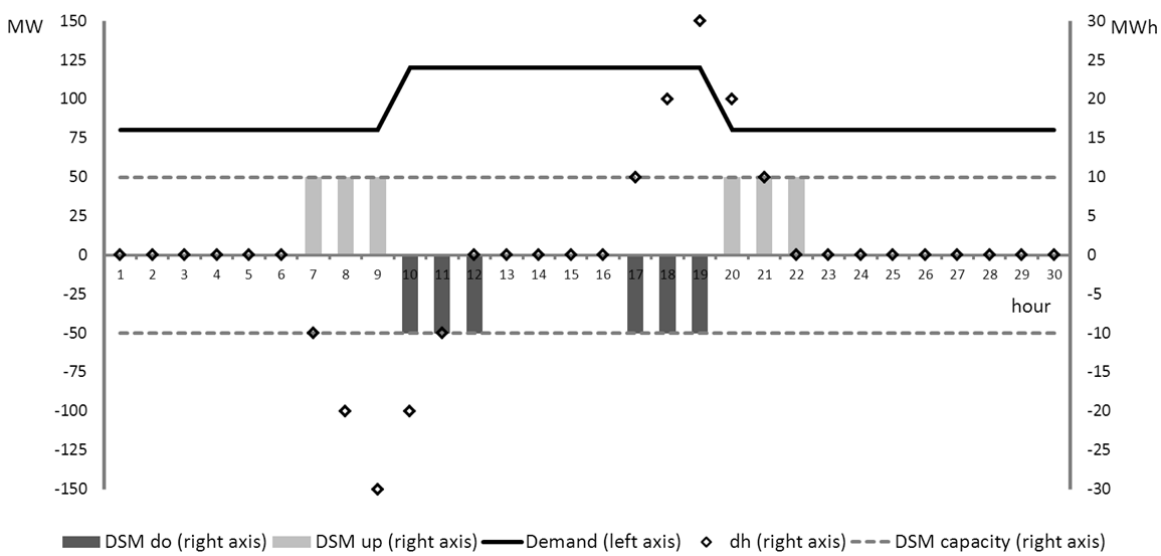
$$DSM_t^{up} \leq C^{up} \qquad \forall t \qquad (8)$$

$$\sum_{t=tt-L}^{tt+L} DSM_{t,tt}^{do} \leq C^{do} \qquad \forall tt \qquad (9)$$

$$DSM_{tt}^{up} + \sum_{t=tt-L}^{tt+L} DSM_{t,tt}^{do} \leq \max\{C^{up}, C^{do}\} \qquad \forall tt \qquad (10)$$

We re-calculate the numerical example presented above, this time with a DSM representation according to equations (7-10). Figure 4 shows that load shifts now occur at both sides of the load distortion, as demand can be shifted up in periods 7 to 9 with corresponding recovery in periods 10 to 12. The figure also includes the cumulative level of demand on hold dh_t for illustrative purposes, although this variable is not necessary for the functioning of the mechanism.[8]

Figure 4: A more realistic temporal structure of load shifts



[8] dh_t is interpreted as a free variable here. Demand on hold is negative in the initial periods as demand is shifted up first.

The real-world applicability of our approach may be further improved, for example by including losses related to load shifting. These could be readily incorporated by including an appropriate efficiency factor η on the left-hand side of (7').

$$DSM_t^{up}\eta = \sum_{tt=t-L}^{t+L} DSM_{t,tt}^{do} \qquad \forall t \qquad (7')$$

Introducing a recovery time may constitute another meaningful extension of the model, as many real-world DSM processes are not allowed to cycle continuously. An additional equation (11) enforces a recovery time R by demanding that the cumulative upward load shift over the whole recovery time does not exceed the maximum upward energy of one DSM cycle. This formulation effectively prevents excessive DSM utilization without requiring, for example, integer variables.

$$\sum_{tt=t}^{t+R-1} DSM_{tt}^{up} \leq C^{up}L \qquad \forall t \qquad (11)$$

4 Conclusions

Demand-side management merits increased attention by power system modelers. With regard to analyses dealing with, for example, fluctuating renewable generation, carbon emissions constraints, network restrictions, or capacity adequacy, it is important to incorporate DSM constraints in a complete and consistent way. Otherwise, the assessment of DSM patterns and related system benefits may be severely flawed. Building on a model formulation put forward by Göransson et al. (2014), we first suggest an improvement that resolves the problem of undue DSM recovery. We further introduce an alternative DSM model that is both concise and linear and increases the real-world applicability of demand-side management modeling. Our formulation could readily be included in a wide range of numerical models dealing with the power system or the energy system as a whole. Our proposal may thus not only contribute to the academic strand of DSM-related literature, but may also foster improvements of applied and policy-relevant modeling activities.

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