FORMULATION OF PARAMETRIC COST-FUNCTIONS FOR ANCILLARY SERVICES FROM DISTRIBUTED RENEWABLE ENERGY RESOURCES IN DISTRIBUTION NETWORKS

Konstantinos Oureilidis1*, Kyriaki-Nefeli Malamaki1, Spyros Gkavanoudis1, Charis Demoulias1

1Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece

*oureili@yahoo.gr

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Abstract

Conventionally, the Transmission System Operators (TSO) make use of the controllable Synchronous Generators (SG) for the provision of ancillary services (AS) in order to ensure the secure and safe operation of the electricity system, especially in case of grid emergency events. However, the increasing penetration of Distributed Renewable Energy Sources (DRES), especially in distribution grids, has resulted in the gradual decommissioning of the SGs, resulting in poor system reaction. The problem is mainly focused on the unavailability of providing AS from DRES, since they are currently regarded as uncontrollable negative loads. Nevertheless, new control algorithms have been emerged for converter-interfaced DRES, which emulate the operation of SGs. Therefore, new markets for trading AS in distribution grid level can be developed, where the DRES would play an active role. Towards this perspective, this paper proposed general parametric cost-functions based on cost-benefit analysis by dividing the AS in three general categories: AS provided by SGs (primary frequency response, voltage control), AS inherently provided by SGs (inertia, fault contribution) and new AS due to the different nature of DRES (power smoothing, harmonic mitigation). The target is to identify the cost related to each AS, in order to configure the market participation strategy.

1 Introduction

Nowadays, the TSOs face the challenge of maintaining the power balance between production and demand due to the increased power from RES and especially from wind and solar energy. The problem becomes more intense in weak grids due to the different nature of the DRES, which is intermittent and stochastic, while the forecast models are still considered non-accurate. Some of the main consequences are frequency drops, congestions in distribution and transmission system level and large voltage fluctuations.

Currently, the Operators (TSO, DSO) consider the DRES as uncontrollable negative loads, without exploiting their opportunity of providing any frequency or voltage regulation. The conventional control algorithms implement the Maximum Power Point Tracking (MPPT) philosophy allowing the participation in energy markets with several market schemes (e.g. feed-in tariff, feed-in premium). Therefore, since the DRES are considered as uncontrollable sources, the TSOs still engage SGs for the provision of AS [1], while the DSOs oblige the active power curtailment in certain cases, in order to keep the voltage and frequency between the predefined limits [2].

However, the gradual displacement of the large SGs placed in the transmission system with smaller-sized DRES of the distribution grid has complicated this situation and raised the concerns of the Operators about the safe and stable operation of the grids. In order to take remedial actions, new grid codes have been emerged, where certain connection rules are imposed for the DRES, e.g. the Puerto Rico Electric Power Authority Code [3]. Furthermore, new control methodologies have emerged, which transform the DRES into active controllable entities, being able to contribute to grid events according to its settings. Such control strategies can be found in [4], [5]. Therefore, the participation of DRES in AS markets can be redefined by considering the costs for providing each AS [6].

Traditionally, the AS markets are operated by the TSOs with organized mechanisms, permitting the recovery of the real costs closer to the AS activation [7]. The costs include the opportunity costs, efficiency costs, wear and tear costs and stability costs [8]. Such categories can also be applied in DRES, by considering their rotating parts (like wind turbines) or converter-interfaced grid connection (like photovoltaics). Furthermore, another important aspect concerns the supplementary cost of the energy storage system with its auxiliary equipment, which is necessary for the provision of AS due to the volatile nature of the DRES.
This paper goes beyond the state-of-the-art by proposing separate cost-functions for the following AS categories: (a) AS provided currently by SGs (primary frequency response, voltage control), (b) inherent AS provided by SGs (inertia, fault contribution) and (c) new AS provided by DRES (power smoothing, harmonic mitigation). The target is to define the efficient operation of the DRES within the distribution grids.

2 Parametric cost-function per AS

In general, the following cost parameters are taken into consideration for the determination of the cost-functions per AS:

- Installation cost of a Fast Energy Storage System (FESS) with its appropriate auxiliary equipment (e.g. DC/DC converter);
- Oversizing factor of the main DC/AC converter of the DRES;
- Increased operational power losses;
- ICT costs.

2.1 AS provided by SGs

2.1.1 Primary-frequency control (PFR)

In order not to jeopardize the stability and robustness of the power systems, the TSOs balance the power production with the demand by enabling extra resources or increasing the power of committed ones. Since the existing DRES neither receive orders in order to increase their power nor they have a controllable governor, they cannot participate in PFR. An obvious solution is to operate constantly below the MPPT, holding in this way capacity in case of an emergency (Fig.1).

This reserved headroom will create an energy opportunity loss $E_{non_inj}$, which can be compensated by the Operator:

$$ E_{non_inj} = \int_{t_en}^{t_dis} P_{MPPT}(t) \, dt - \int_{t_en}^{t_dis} P_{inj}(t) \, dt \quad (1) $$

where $P_{MPPT}(t)$ is the MPPT, $P_{inj}(t)$ is the injected power, $t_en$ and $t_dis$ are the enabling and disabling instances, respectively. The quantity of the injected power is measured at the Point of Common Coupling (PCC) of the DRES, while the MPP can be estimated by considering the different technology type of the DRES and weather forecasting parameters, such as solar irradiation, wind speed, etc. The lost opportunity cost of the non-injected energy $C_{non_inj}$ can be defined as follows:

$$ C_{non_inj} = E_{non_inj} \cdot CP \quad (2) $$

where CP is the clearing price of the participating market (e.g. Day-Ahead Market, Intra-Day Market) expressed in €/kWh. However, the out-market support compensation $C_{supp_mech}$ should also be considered, which is differentiated in national level [9]. Therefore, the overall opportunity cost $C_{PFR}$ can be summarised as:

$$ C_{PFR} = C_{non_inj} + C_{supp_mech} \quad (3) $$

![Comparison of different PFR reserve techniques for a wind turbine](image)

2.1.2 Voltage control with reactive power exchange

Conventionally, the voltage issues in radial distribution grids are mainly encountered at the last nodes, due to the loads. However, the increasing penetration of DRES caused the opposite effect of the overvoltages. A solution to this issue is the exchange of reactive power at DRES level. In order to ensure that the DRES injects the nominal power to the grid and not curtail active power, the DRES converters should be oversized. In [9,10] different scenarios of PV and wind are examined for defining the maximum reactive power. Following [11], a maximum oversizing factor $D=1.41$ can be considered. The converter oversizing factor increases the installation costs for the DRES, which differs significantly according to the DRES installed capacity. From manufacturers’ datasheet [12], the DC/AC converter cost of a PV of 10kW is regarded to be 160€/kW, while for a large PV of 100kWp is approximately 70€/kW.

However, the operation under a different power factor (PF) than unity will increase the DC/AC converter losses $P_{loss,v}$. In [13], these losses are calculated in analytical form:

$$ P_{loss,v} = c_1 + c_2 \frac{P_o}{P_{PP}} + c_3 \frac{P_o^2}{P_{PP}^2} + P_o \left( c_4 + c_5 \frac{P_o}{P_{PP}} \right) \cdot \left( \frac{2\gamma(P_o)^P_o}{S_b} \cdot \cot \varphi + 1 \right)^2 \quad (4) $$

where $P_o$ is the output power, $S_b$ is the rated power of the converter, $\gamma$ is the output filter reactance, $\varphi$ is the angle between the voltage and the current and $c_i$, with $i=1-5$ are coefficients selected for the various operating PF. The cost of the increased power losses $C_{loss,v}$ can be expressed by:

$$ C_{loss,v} = P_{loss,v} \cdot CP \quad (5) $$

Therefore, the overall cost $C_v$ for providing reactive power:

$$ C_v = C_{oversize} + C_{loss,v} \quad (6) $$

where $C_{oversize}$ is the cost of oversizing the DC/AC converter.

The reactive power exchange has also certain benefits for the DSO. For example, the need for active power curtailment of DRES is minimized. This benefit $B_{curt}$ can be described by:
where \( P_{\text{nom}} \) is the nominal power and \( P_{\text{curt}} \) is the curtailed active power. In the worst-case scenario of DRES disconnection \( B_{\text{curt}} = P_{\text{curt}} \cdot CP \).

Another benefit in DSO level concerns the decrease in the number of tap-changing in MV transformers. This benefit is difficult to be estimated, since maintenance data from DSOs are needed.

2.2 AS inherently provided by SGs

2.2.1 Virtual inertia

In the first few cycles of a power imbalance, the conventional SGs inherently change the speed of the rotor in respect to the synchronous speed due to their inertia. This known physical reaction is not applied to converter-interfaced DRES. In order to overcome this issue, new control algorithms with fast energy systems have been emerged for providing virtual inertia to inertia-less converter. In respect to the synchronous speed due to their inertia. This conventional SGs inherently change the speed of the rotor in the first few cycles of a power imbalance. The inertia droop curve is depicted in Fig. 1.

In order to determine the SC size, the rate of change of frequency (ROCOF) lower threshold for releasing energy \( R_{th1} \) and higher threshold for absorbing energy \( R_{th2} \) should be defined [17]. As shown in Fig. 1, the rate of energy can be adjustable determined by a droop curve with variable inclination, since \( P_{\text{MPP}} \) can vary from 0 up to \( P_{\text{nom}} \):

\[
P = \frac{P_{\text{max}} - P_{\text{MPP}}}{R_{th1} - R_{th2}} \text{ROCOF} + \frac{P_{\text{MPP}} R_{th1} - P_{\text{max}} R_{th2}}{R_{th1} - R_{th2}}
\]

where \( P_{\text{max}} \) is the maximum short-term power capability of the converter, which can be 3-5 times the nominal power of the DC/AC converter.

The inertia \( H \) can be calculated by determining the value of the parameter \( R_{th2} \):

\[
H = \frac{\Delta P}{2 \cdot \text{ROCOF}} = \frac{P_{\text{max}}}{2 \cdot R_{th2}}
\]

The maximum time duration regarding the inertia event can be considered of about 10s. Thus, the maximum stored energy can be calculated by using (9) as:

\[
E_{\text{SC, inertia}} = \int_{0}^{t} P_{\text{max}} d\tau = 2 \cdot H \cdot R_{th2} \cdot 10
\]

In most applications, in order to create an equal capacitance \( C_f \) at a certain voltage level \( U_f \), there are equipped \( m \) parallel and \( n \) series SC units. Therefore, the stored energy is:

\[
E_{\text{SC, inertia}} = \frac{1}{2} n \cdot m \cdot C_f \cdot U_{f, \text{max}}^2
\]

where \( U_{f, \text{max}} \) is the maximum voltage of the SC unit.

An extra cost is also applied for the necessary connection cables and microelectronics. These costs usually vary between 55% and 75% of the total SC cost. Therefore, considering an average factor of 60% or 1.6 of the nominal SC cost, the total cost equals to:

\[
C_{\text{inertia}} = 1.6 \cdot C_{SC}
\]

2.2.2 Fault contribution

Regarding any fault within the distribution grid, the DRES are obliged to disconnect in order not to interfere the operation of the protection means. However, since there is a lack of large short-circuits currents due to the gradual decommissioning of large SGs, this practice seems outdated. On the other hand, by employing the proper control strategies, the DRES can contribute to fault clearing by injecting short-circuit currents equal to a few times the nominal one, as in Fig.2. In order to overcome the possibility of any partial or full unavailability of the primary DRES source, a FESS (e.g. SC bank) can be added.

The estimation of the SC bank \( C_{SC,f} \) will be considered for the worst-case scenario, which concerns a high-impedance fault. In such kind of faults, the remaining voltage is relatively high and the DRES needs more power for the fault clearing. Considering a fault time duration equal to \( t_f \) and the needed power for the fault clearing process is \( P_f \), then the stored energy of the SC \( E_{SC,f} \) will be estimated as:

\[
E_{SC,f} = \frac{1}{2} C_{SC,f} \cdot V_{SC}^2 = \frac{1}{\eta} P_f \cdot t_f
\]

where \( V_{SC} \) is the voltage of the SC, \( \eta \) is the overall efficiency of the DRES DC/AC converters.

It should be mentioned that the faulty currents are location-sensitive, therefore the relevant distance between the DRES and the fault should be regarded in the design of the protection means. A cost estimation for the SC bank is approximately equal to 10% of the respective DC/AC converter [18].
2.3 New AS provided by DRES

2.3.1 High frequency power smoothing

In case of weak distribution grids, the degradation of the power quality due to high DRES penetration has resulted in certain frequency and voltage issues, such as flickering. Therefore, new grid rules impose a limitation on the power by a ramp rate \( r_{sm} \) (e.g. 10%/min) \[3\]. In order to implement this power smoothing, a FESS, such as SC, should be connected. By employing a simple power smoothing algorithm, the SC bank \( E_{SC,sm} \) can be indicatively calculated for the worst-case scenario, which corresponds to the absorption of the DRES nominal power \( P_{nom} \) for the time period \( \Delta t \):

\[
E_{SC,sm} = r_{sm} \cdot P_{nom} \cdot \Delta t \quad (14)
\]

The total cost is of SC is equal to:

\[
C_{SC,sm} = E_{SC,sm} \cdot CP \quad (15)
\]

\[P_{T}(I) = \theta[a_T + (b_T + c_T)I + (d_T + e_T)I^2] \quad (16)\]

\[P_{d}(I) = \theta[a_d + (b_d + c_d)I + (d_d + e_d)I^2] \quad (17)\]

where \( P_T(I) \) is the power loss of the power electronic switch (e.g. IGBT), \( P_d(I) \) the power losses of the diode, \( I \) the RMS value of the output current, \( \theta \) is the temperature and the coefficients \( a_{i,d}, b_{i,d} \) and \( c_{i,d} \) (where \( i=T, d \)) are coefficients representing conduction and switching losses of the electronic power devices. Therefore, the sum of the power losses can be expressed by combining (16) and (17):

\[
P_{loss,hm} = P_{T}(I) + P_{d}(I) \quad (18)
\]

The high order distorted currents also increase the power losses of the distribution grid transformers. The power losses are categorized in copper losses, which depend on the current and magnetizing losses \[20\]. Therefore, the increased copper losses \( P_{cu,inc} \) can be estimated as:

\[
P_{cu,inc} = P_{cu,naf} - P_{cu,af} \quad (19)
\]

where \( P_{cu,naf} \) are the copper losses without the operation of active filter and \( P_{cu,af} \) are the copper losses with active filtering. Therefore, the aggregated cost \( C_{hm} \) for providing harmonic mitigation is:

\[
C_{loss,hm} = (P_{loss,hm} + P_{cu,inc}) \cdot CP \quad (19)
\]

3 ICT cost-analysis

The costs related to ICT can be separated in the following categories:

- Hardware/Network costs
- Communication costs
- Software/license costs
- Encryption costs
- Personnel costs

These costs concern the development and operation of the new infrastructure of the control area, enabling the DSO to rend/receive the respective information and control signals. Therefore, new equipment, such as servers, virtual machines and switches should be installed.

Regarding the communication, the most common channels are the mobile communication or internet. A very important pollution in distribution grids \[19\]. A solution to this issue is the development of active filtering control algorithms, in order the DRES to inject the properly distorted currents and maintain the total harmonic voltage factor within the limits of the standards.

The related costs here regard the increased power losses of the converters due to the provision of distorted currents. By considering the DC voltage and the switching frequency constant, the power losses of a power electronic switch, such as IGBT, can be calculated by the following equations \[13\]:

2.3.2 Harmonic mitigation

Another issue emerged by the high proliferation of converter-interfaced DRES is the increase of the harmonic
part regards the security of the information from cyberattacks, which implies extra encryption costs.

4 Conclusion

This paper proposes the participation of the DRES in the provision of AS at distribution grid level. Both existing and new AS are provided in parametric way by conducting a cost analysis. Since the DRES present a volatile and intermittent nature, auxiliary storage systems should also be added, which cost may differentiate according to nominal capacity and voltage level. Other cost factors are related to the operation below the maximum power, the oversize of the converters, the ICT costs and the increased losses in order to provide AS. All these cost parameters should be evaluated together with the benefits of the DSO, in order to result to an efficient operation of the DRES.

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