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Aggregation Strategy for Reactive Power Compensation Techniques—Validation

Jibran Ali [1,*], Stefano Massucco [2] and Federico Silvestro [2]

1 MEAN4SG & DITEN—University of Genoa, via all'Opera Pia 11a, 16145 Genova, Italy
2 DITEN—University of Genova, via all'Opera Pia 11a, 16145 Genova, Italy; stefano.massucco@unige.it (S.M.); federico.silvestro@unige.it (F.S.)
* Correspondence: jibran.ali@edu.unige.it or jibranali.mean4sg@gmail.com; Tel.: +39-351-096-1985

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Abstract: Reactive power provision is a vital ancillary service, which provides opportunities to service market and power generators. The net reactive power in a balanced power grid needs to be zero, and the imbalance occurs due to the capacitive and inductive behavior of the extensive transmission lines, and because of the intermittent behavior of load-demand. This mismanagement in reactive power causes voltage instability, and hence the paper compares the most common reactive power compensation techniques, which are prevalent in both literature and commercial levels. The paper perceives the trade-off between the compared techniques, and realizes to use the aggregation of different techniques to present a coordinated control mechanism that complies with the Italian regulations. The parameters for the proposed aggregation include the amount of reactive power, real power losses during reactive power provision, and response time. The paper then implements IEEE 9 bus transmission-generation system in DIgSILENT to set up the platform for validation of the proposed strategy. Finally, it simulates Transmission System Operator (TSO) test cases on the implemented test system.

Keywords: DIgSILENT; power system; reactive power; voltage profiling; ancillary services; transmission system operator (TSO)

1. Introduction

Wind and solar resources are ponderously integrated in the distribution grid due to the high possibility of incentives, which causes the dynamic changes in the distribution system [1–4]. System operators do not have direct influence on these changes, as the addition is not fully visible to them with a reduction in hosting capacity [5], as calculated in [6]. As a result, the power system faces many complexities, like changes in over-current protection schemes due to the facts that are discussed in [7,8]. The effects on system reliability are discussed in detail in [9,10].

System stability, their limitations, and challenges that are associated with penetration of renewable resources are available in [11,12]. Voltage stability and, in particular, voltage loading, is affected, as in [13], which used storage system for the voltage management. The concepts of voltage stability, its importance, and implications on power system are inferred from [14]. References [15,16] discuss the voltage fluctuations and the violations of over voltage and under-voltage limits due to these intermittent renewable resources. These voltage quality issues and their effects are further supported by [17,18], with an emphasis on problems for TSO. Amongst all of the issues, voltage deviations at the power system buses are the points of focus in this paper. These voltage deviations are due to the reactive power mismatches at transmission networks and loads. The basic principle of equality in reactive power generation and its consumption is violated, which leads to voltage profiling issues.

Reactive power balance is a vital ancillary service [19,20], as the integration of renewables make the voltage loading issue more dynamic. Reactive power management is the key towards ensuring voltage stability, as demonstrated in [21]. In other words, reactive power imbalances at the power grid cause voltage instability and loading violations. The power system can even suffer catastrophes, such as blackouts and contingencies that are due to these imbalances, as described in [22]. The two main mismatch creators are the transmission networks and the load side varying demand, as in [23–25]. In Italy, Transmission System Operator (TSO) controls this mismanagement under ancillary services provision. TSO takes this provision from conventional generators as mandatory provision [26]. The paper follows Italian conventions, and later performs validation for reactive power mismatches only at the transmission level.

In current practices, synchronous Generators (SG) that are operated under conventional power plants are used for overcoming these mismatches. However, there are other reactive power management techniques as both market and research solutions. However, the policies vary for the TSO of each country, and thus the nature of their use varies accordingly. Their use is further dependent on the parameters of cost (installation and operational), efficiency, they quantity of support, and the ease of adaption. The application area of power system further limits the use [27,28].

Some literature discussions are on Voltage Regulation Distribution Transformer using On Load Tap Changer [29], Automatic Voltage Regulator (AVR) at generation side [30], and fuzzy logic based coordinated Power System Stabilizer (PSS), together with AVR at the generation side [31]. Others include synchronous Condensers (SC) with techno-economic analysis in [32,33], mechanically switched capacitors [34], and coordinated control between the switched capacitors and Static Synchronous Compensator (STATCOM) to avoid square voltage fluctuations [35].

Other techniques involve inverters for improving static voltage stability [36], storage system [37], and wind and solar converters that are already installed in the wind and photovoltaic farms, as in [38]. The requirements for their functionality, the trade-offs, and the amount that they can provide are discussed in [39]. A better comparison that involves different techniques and criterion is provided in [40,41]. Reference [42] shows how well designed reactive power sources can be efficiently used for voltage control within and advanced control scheme. It also shows how the effective use of reactive power sources could decrease expensive emergency control actions, such as load shedding (though multi-step control and different weights assigned to different controls). This fact is the motivation towards aggregation approach, as there is aim for the better control of the system in terms of avoidance of expensive controls [42]. Table 1 summarizes the comparison in terms of costs, efficiency, and reactive power capability. Synchronous generators are the most efficient (with very low active power loss due to reactive power provision), and they can provide a high amount of reactive power. However, the associated capital and operating costs are very high. Synchronous condensers can further reduce the capital costs, with the fact that use is from the available synchronous generators, which only requires the conversion costs. With capacitors, it requires many shunt combinations to satisfy the TSO requirements, and the efficiency is degraded with increase in voltage levels (reactive power following square voltage dependency). Thus, FACTS (Flexible AC Transmission Systems) and inverter-based technologies are compared, as in [43,44], to explore their tendencies. The concept of the paper is to utilize these techniques on top of conventional technique of SG, and to aggregate them in the best possible way [1,45–49].

The paper is divided into five sections. Section 2 proposes the aggregation technique, with better steady state response, transient response, costs, and amount of provision, in order to facilitate power plants on TSO requests. The next step is to endorse feasibility of the proposed technique, for which Section 3 describes the simulation model, test case, and the platform for validation. Section 4 covers validation of the strategy, and elaboration and analysis of results. Section 5 concludes the paper, with indications of potential future work.

Table 1. Reactive Power Compensation Techniques.

Reactive Power Compensation Mechanism	Costs (Overall)	Efficiency	Reactive Power Capability
Synchronous Generator	Very high (specially the capital costs)	Very high	High
Synchronous Condenser	High (both capital and operating costs)	Very high	High
Capacitors	Low	Very high	Low
Static VAR Compensator (SVC)	Average (but the capital costs are high)	High	Low
STATCOM	Average (but the capital costs are high)	Low	Average
Inverters within Wind-PV Farms	Low (specially the operating costs)	High	Lower than SVC

2. Proposed Coordinated Strategy

Since each technique for reactive power has trade-off in its performance, the section is devoted to propose a coordinated strategy. The strategy should follow the requests of TSO in the best possible way. TSO procures the service of reactive power from conventional generation units for the following reasons:

- Quick service is required in the case of contingencies and urgencies.
- Huge amount is required in the case of huge deviations.
- More efficiency is required to justify the better use of resources.

Therefore, TSO requires a strategy that meets the VAR (unit of reactive power) requirements in the best possible way. The strategy initiates with these two points to support the service with low losses, high amounts, and quick restoration:

- Use of SG for normal conditions, with the addition of synchronous condensers for high steady state reactive power requirements.
- Addition of STATCOMs for more fast provision.

This initialization leads to four different cases: Normal conditions with SG, the use of additional SG only for any reactive power needs, the addition of synchronous condensers for more provision, and the addition of STATCOM for better transient response. Figure 1 explains the initialization of the strategy, with an elaboration of TSO requirements. The arrows with yellow indicate the type of service from power plants, as requested by TSO. In response to these requests, the control center at power plants can take service from red arrow (SG as mandatory provision for low losses), green arrow (Synchronous Condenser for huge amounts), and blue arrow (STATCOM for fast response).

TSO decides for this provision through the flexibility curve generated at their controllers. The plot in Figure 2 characterizes the strategy-curve, which comes from the following aspects:

- The use of capacitor banks is eliminated, because reactive power depends on square of voltage, and hence it is not suitable for high and medium voltage applications.
- SVC is also eliminated due to the voltage non-linear dependency and the associated high costs for the investment.
- Inverters are skipped too due to the very low provision.
- Synchronous generators and synchronous condensers are the best in terms of steady state response.
- STATCOM performs best for the transient cases.

The strategy is mapped with four regions of operation. Region 1 is to guarantee fast response in transient conditions with STATCOM. Region 2 incorporates more use of synchronous generators in order to reduce the operating losses. Region 3 incorporates more use of synchronous condenser in order to reduce the capital costs and to give more flexibility to power plants. Region 4 is the use of all these techniques to satisfy the TSO requirements in an optimal manner.

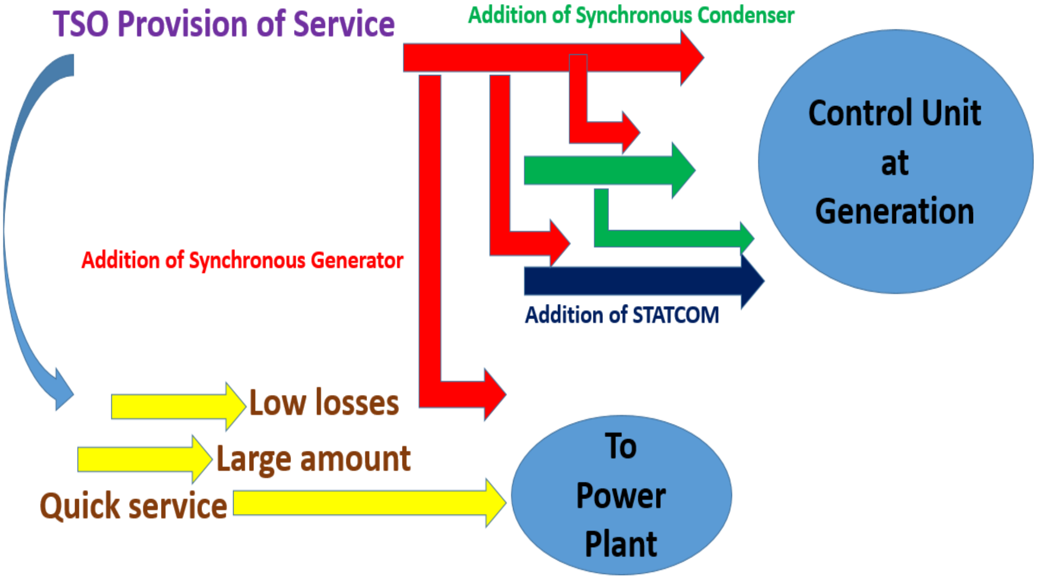

Figure 1. Transmission System Operator (TSO) needs vs. Approach of controller.

Region 4 is the prospective one that is to be used in the future. It allocates the added flexibility with regard to advantages of high service provision in both the transient and steady states, with most favorable costs and efficiency. Each one of these regions are visible to both generators and TSO (with a controller-based interface at power plant). Figure 3 describes the benefits of the proposed strategy in terms of speed of response (time taken to arrive maximum provision of SG, named as P1, vs time taken by STATCOM only for the same provision), flexibility (reactive power demand by TSO vs provision by SG only at P1), and the associated capital and operating costs (taken from [1]). All of the comparisons are based on base value of 1. All of these regions need to be validated in order to endorse the feasibility of the presented mechanism. The proceeding section describes the test cases and the platform for validation.

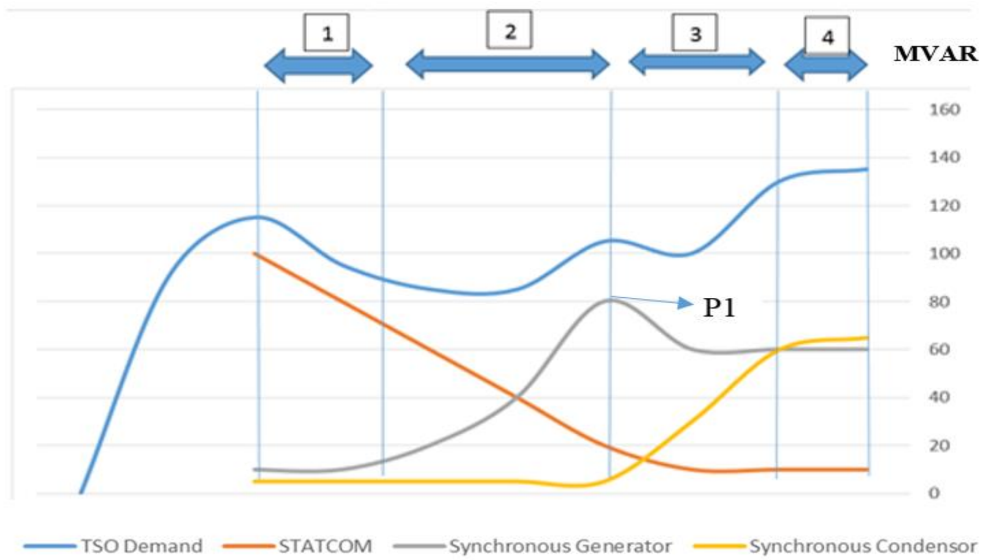

Figure 2. Proposal for Aggregation strategy.

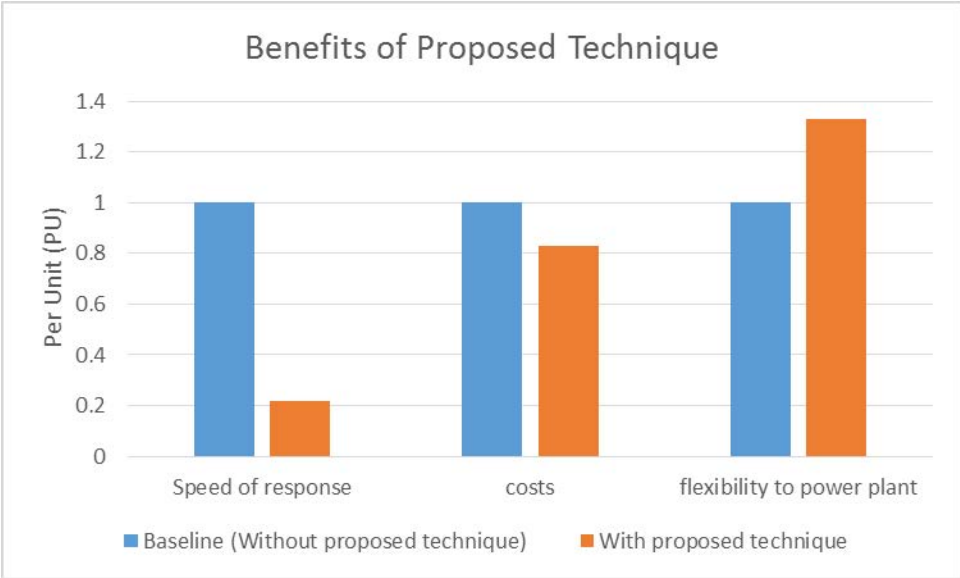

Figure 3. Benefits of Aggregation strategy.

3. Test System Modeling

The test system includes the electrical interface of a power plant, under the supervision of TSO at the Point of Interconnection (POI) with conventional generators and representative transmission network. At the electrical output end of power plant, a step-down transformer is used at POI. The compensation devices are added at the lower voltage end of transformer to comply with their operational ratings. The IEEE 9 bus conceptual system displayed in Figure 4 is used as the reference transmission network, which is used to demonstrate the reactive power mismatches with reference to the demand and transmission lines. The reference IEEE model is studied from [50,51], and the DIgSILENT implementation is taken from [52]. Load A is selected as the source of load variations, and line 8–9 as the representative transmission line. Generator 3 is selected as the representative coal-fired power plant, where the reactive power compensation devices are installed.

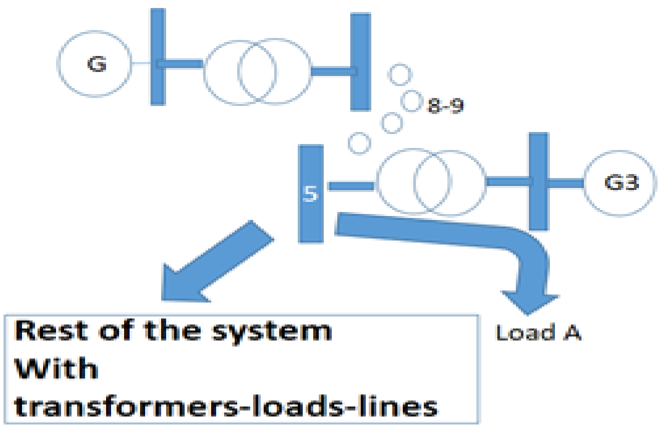

Figure 4. IEEE 9-bus conceptual system.

The coal-fired power plant generates electrical output, with input mechanical energy as coal. In the context of this paper, the electrical output is the only point of interest, which is assumed to have an operating real power up to 200 MW, reactive power, and voltage value. However, the model is used from the DIgSILENT database, as in [52]. For the ease of analysis, the AVR and the primary frequency control libraries are directly used from [52]. However, secondary frequency control is not used and PSS is used for that purpose.

The DIgSIENT model in [52] used the reference data from [51]; however, the data set is changed in the context of this paper. The changes, with implementation, are indicated in the proceeding section. The next point is the definition of test cases for TSO services on this platform. Table 2 elaborates on the test cases, which complies with the following TSO actions at POI:

- Increase/decrease in reactive power for fast provision.
- Increase/decrease in reactive power for high provision.
- Increase/decrease in reactive power for distant provision. As reactive power is a local ancillary service, and for geographically distant (far) locations, the control has to be changed.

Table 2. Look-up table for TSO mismatches.

Serial No.	Point(s) of Variation	Increase or Decrease of Reactive Power?	TSO Visibility for the Variation
1	Bus/Node 5 (Load A)	Increase	Decrease in demand, i.e., the distribution system requires inductive reactive power
2	Bus/Node 5 (Load A)	Decrease	Increase in demand, i.e., the distribution system requires capacitive reactive power
3	Line from node 8 to node 9	Increase	Capacitive effect dominates on transmission network
4	Line from node 8 to node 9	Decrease	Inductive effect dominates on transmission network
5	Bus/Node 5 (Load A) and Line from node 8 to node 9	Increase	Overall reactive power mismatches, requires inductive reactive power
6	Bus/Node 5 (Load A) and Line from node 8 to node 9	Decrease	Overall reactive power mismatches, requires capacitive reactive power

Table 2 is used as a look-up for the mismatches at TSO and the reactive power mismatch use cases. The point of variation is the point, which is the source of reactive power mismatch and can both be in incremental and detrimental ways. This effect is explained under "TSO visibility for the variation" from the perspective of TSO. In this paper, an increase in reactive power means the capacitive effect of reactive power and a decrease in reactive power means the inductive effect of reactive power (in principle the generator convention).

4. Validation of the Proposed Strategy

Following the data-set description, for the system in Figure 4, in the previous section, the changes are indicated here. The loads at bus 5 can consume up to 100 MVAR, and they can generate up to 100 MVAR too. In other words, the loads are representatives of their inductive reactive power nature, but also include the transmission level co-generators with capacitive effects. This is seen as the equivalent demand change, as represented with this load set. The real power has a rated value of 250 MW. For the Line 8–9, the base values of X and B are assumed 30 Ohms and 300 micro-Siemens. The line can endure the test sets up to 50 Ohms and 450 micro-Siemens to represent variations in reactive power w.r.t inductive (X) and capacitive (B) variations. Generator 3 has a rated real power of 140 MW and a rated reactive power of 50 MVAR.

Four simulation cases are simulated in DIgSILENT, as described in the previous section. The results are elaborated one after another. Table 3 mentions the inputs for all four cases. Table 4 provides line and transformer loading, which verifies that there is no issue of over-loading of lines and transformers. Table 5 provides the node voltages for all the cases in Per-Unit (PU).

Table 3. Definition of Input.

Serial No.	Element	Values of Dataset
1	Load A at Bus 5	Real power = 250 MW, Reactive power = 50 MVAR
2	Line 8–9	X = 30 Ohm, B = 300 Micro-Siemens
3	Generator at Node 3	Real power = 140 MW, Reactive power = 50 MVAR
4	Additional Synchronous Generator at node 3	Real power = 140 MW, Reactive power = 70 MVAR
5	Synchronous Condenser at node 3	Real power = 140 MW, Reactive power = 70 MVAR
6	STATCOM at node 3	Reactive power = 70 MVAR (inductive/capacitive)

Table 4. Quasi-dynamic simulation report (loading range).

Serial No.	Element	Maximum Loading in %
1	Transformer 3	83.725
2	Transformer 2	73.273
3	Transformer 1	56.647
4	Line 4 to 5	32.089
5	Line 5 to 7	30.225
6	Line 6 to 9	21.639
7	Line 8 to 9	21.334
8	Line 7 to 8	11.114
9	Line 4 to 6	9.911

Table 5. Quasi-dynamic simulation report (voltage range).

Bus	Voltage Min. [PU] without Compensation	Voltage Max. [PU] without Compensation	Voltage Min. [PU] with SG Only	Voltage Max. [PU] with SG Only	Voltage Min. [PU] with SG & SC	Voltage Max. [PU] with SG & SC
3	0.910	1.206	0.712	1.184	1.092	1.116
9	0.927	1.180	0.977	1.161	0.967	1.068
8	0.968	1.140	0.991	1.123	0.975	0.995
2	0.905	1.127	0.996	1.113	0.901	0.966
7	0.995	1.127	0.913	1.113	0.901	0.967
6	0.921	1.088	0.976	1.078	0.911	0.976
4	0.911	1.058	0.988	1.054	0.975	0.977
1	0.981	1.040	1.011	1.04	0.968	1.040
5	0.916	1.039	0.956	1.031	0.915	0.977

No additional compensation device is used in the first case. The results in Table 5 clearly reflect over-voltage violations at most of the buses (i.e., bus 2, 3, 7, 8, and 9), with reference to the fact that transmission system operators are bound to ensure upper voltage variations up to 10%. The next case aims to involve synchronous generator as additional compensation device. The results in Table 5 clearly reflect over-voltage violations again at most of the buses (i.e., bus 2, 3, 7, 8, and 9), with reference to the fact that transmission system operators are bound to ensure voltage variations up to +10% and −15%. However, the maximum voltage variation at bus 3 is reduced by around 1.8% by the addition of a synchronous generator. The percentage of over-voltage is reduced at most of the buses, and hence it complies with the "Reactive power provider" mode of synchronous generator. For the minimum voltage, most of the buses get a boost in voltage to increase the margin for under voltage violation, with a maximum margin of 10% at bus 2. However, there is a contradictory effect at two buses 3 and 7, where the minimum voltage is further reduced and this can be alarming for system operators to ensure the under-voltage limits. The worst effect is at bus 3, where the under-voltage violation takes place. However, this issue can be resolved by the use of further compensation (either by

SG or by aggregation). In addition, reactive power is better as a local control, and TSO can easily manage the changes at bus 3 (point of compensation). This is later shown in the case with STATCOM.

The further addition of reactive power capacity through conventional power plants can avoid these over-voltage violations; however, this puts a lot of burden and responsibility on these power plants (normally coal and combined-cycle). The next case is used to analyze the same plant with an additional synchronous condenser in order to give flexibility to these power plants. Thus, synchronous generator and synchronous condenser are employed as compensation devices. It is clear from the results in Table 5 that the addition of synchronous condenser overcomes the over-voltage issue at almost all pf the buses, except for bus 3. The problem of under-voltage violation is also overcome at bus 3. The over-voltage violations are reduced up to 14% w.r.t base case, and up to 13% w.r.t SG compensation. At low voltage levels, most of the buses decrease their voltages and pose risk to the under-voltage limits. However, the variation is up to 9% maximum and there still remains around 6% margin for under-voltage limits. The existing issue is the 1.116 PU maximum voltage at bus 3, and the idea is to use flexibility of STATCOM to the bus 3 violations, by operating the STATCOM at POI. The problem can also be resolved by installing a shunt capacitor bank at bus 3. This gives three advantages:

- There is no need to operate the STATCOM at POI, in order to avoid the operational and maintenance costs.
- The capital cost for STACOM installation at POI is very high.
- Capacitor bank gives a fast response, and almost linear response when compared to STATCOM.

However, the solution is not feasible in the case of violations at most of the buses, at POI, or the violations are huge in magnitude. Therefore, a trade-off is there in terms of costs and reliability. The next case is to install STATCOM at POI to ensure further flexibility and a better transient response. This involves STATCOM on the top of the previously employed compensation techniques. The graphs reflect the improvements with STATCOM: Figure 5 shows the response before the addition of STATCOM, whereas Figure 6 displays the STATCOM added behavior.

It is clear that the voltage loading at node 3 is improved with the addition of STATCOM. Without the use of STATCOM, the voltage goes above 1.1 PU for 57% of time that is the violation of over-voltage limits. The addition of STATCOM eliminates this over-voltage violation for 100% time scale. The static simulations for initial one hour is shown in Figure 7 in order to better visualize the effects of STATCOM on node 3 voltage, where the voltage shifting is clearly visible.

The next step is to test the transient behavior of voltage at buses for the achieved setup, with introducing another load at bus 5 with the similar characteristics of previous load. The changes to reactive power are compared with two cases: (1) With the use of additional SG and SC, (2) With the use of additional SG, SC, and STATCOM. The time to reach voltage limits, after the over-voltage violation, is noted for each bus; the results are plotted in Figure 8. From the figure, it is clear that STATCOM improves the transient performance, which is effective for a faster response to TSO requests.

The results demonstrate that reactive power is essential for voltage stability, and the coordinated mechanism for the use of STATCOM, synchronous generators, and synchronous condensers is validated. The applications depend on the specific TSO applications for a specific region. Applications may involve a typical current solution with a trade-off amongst reactive power provision and capital/operating costs. It may be the least cost-effective option, but with high availability. Another one can be the low-cost solution, but with reduced applicability to the power plants. The reason is the insufficient amount for participation in the ancillary service market. The application may cover potential future solution with the best possible reactive power reserves.

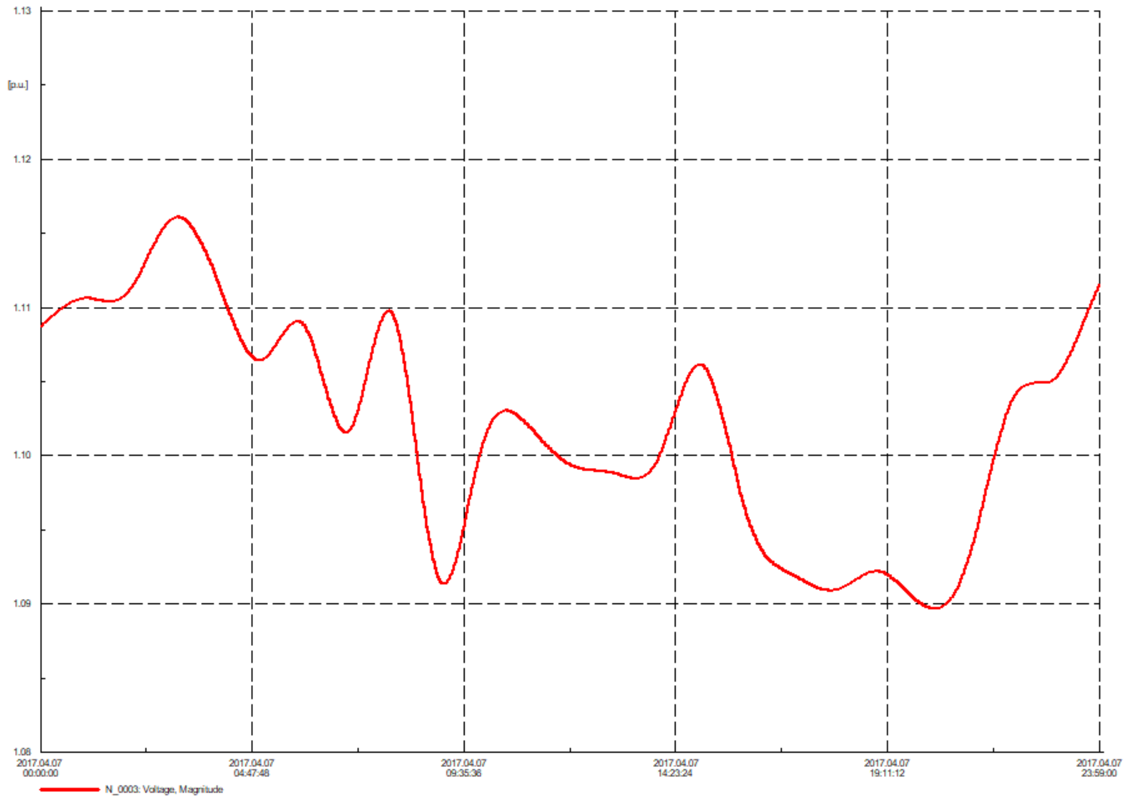

Figure 5. Voltage at bus 3 before addition of Static Synchronous Compensator (STATCOM).

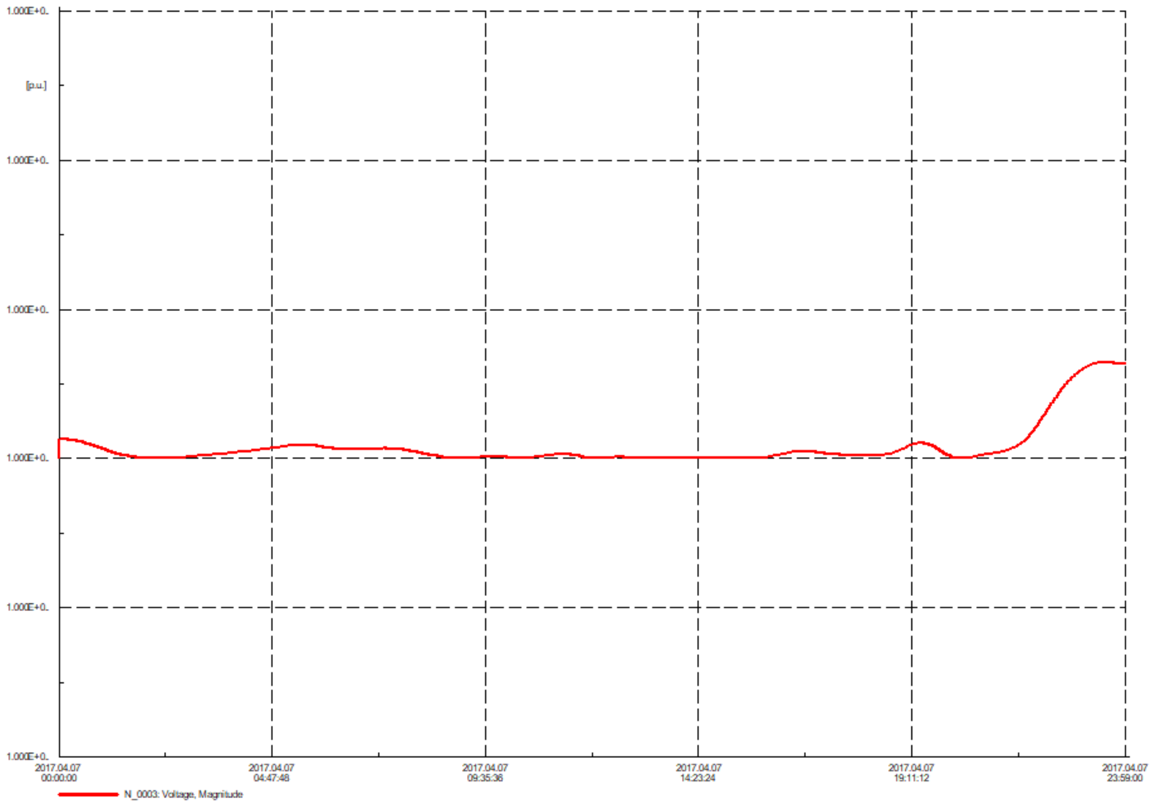

Figure 6. Voltage at bus 3 after addition of STATCOM.

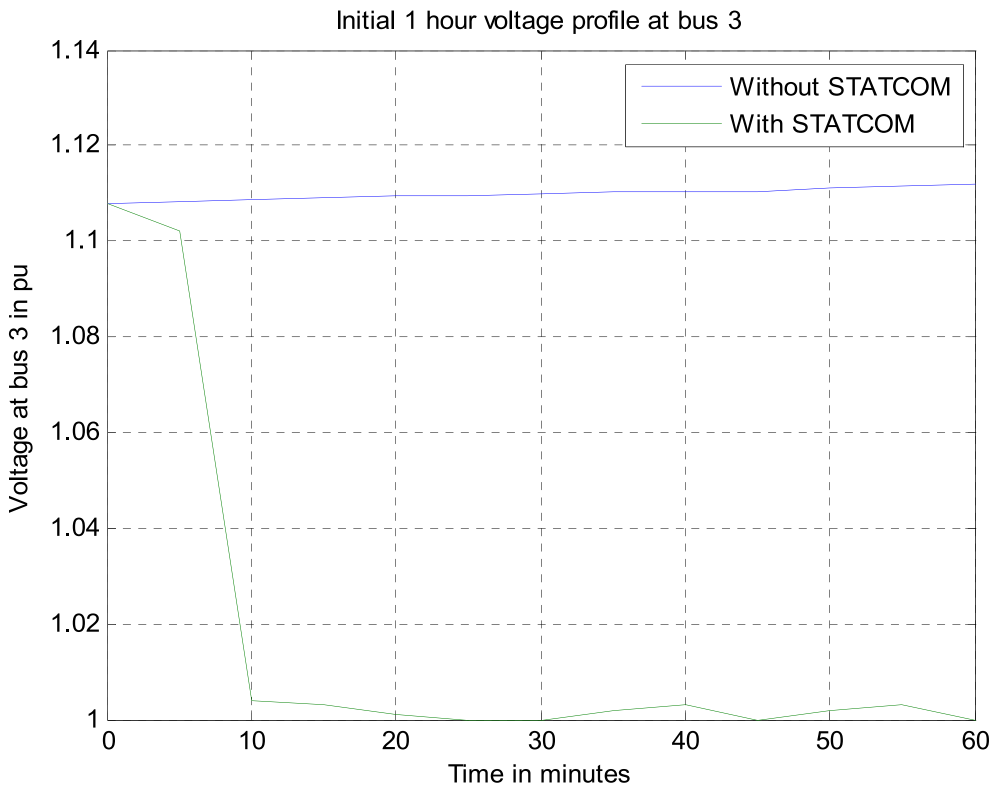

Figure 7. Node 3 voltage with/without STATCOM (one hour profile).

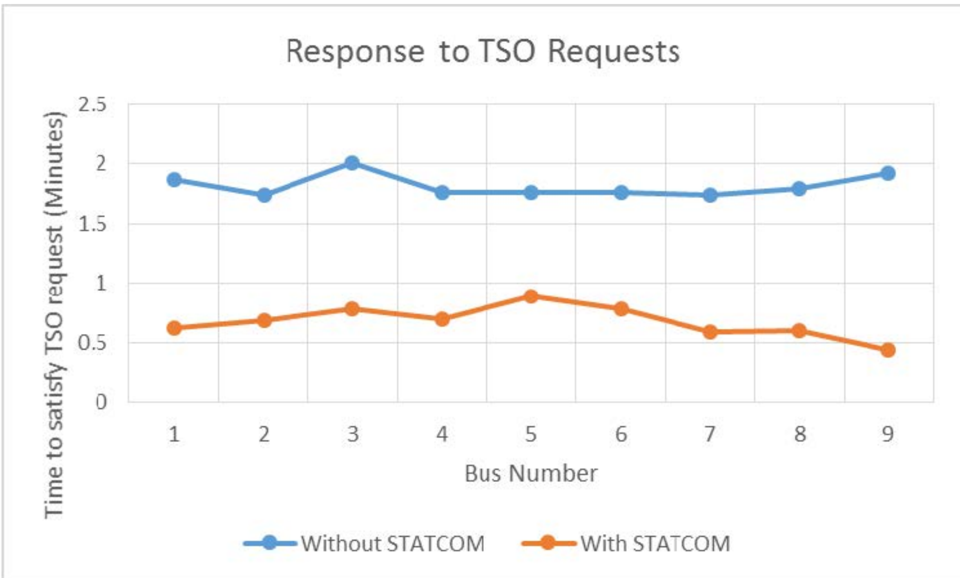

Figure 8. Response time to TSO with/without STATCOM.

5. Conclusions

The paper presents a coordinated strategy that can utilize the aggregation of different reactive power compensation techniques to fulfill the TSO demands in the best possible way. The strategy is developed according to Italian TSO requirements, and the paper validates the strategy, with the implementation of IEEE based transmission model in DIgSILENT, on TSO test cases.

The proposed strategy in the paper is designed for conventional power plants, as the Italian regulatory barriers do not allow for distributed energy resources, DSO, and inter-aggregated zones to contribute towards the provision of ancillary services. Moreover, Italian TSOs do not remunerate power plants for this service of reactive power, so the main business strategy for these conventional units is to ensure flexibility. The results ensure that, in order to make the power plants and TSO more flexible for the provision of reactive power, it is useful to integrate different technologies to coordinate the provision. Future work includes the extension of the strategy to other ancillary services.

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