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A predictive agent-based scheme for post-disturbance voltage control

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ABSTRACT

In this paper a predictive scheme for dynamic voltage control is proposed, which maintains voltage security (both voltage stability and voltage profile) of power system, in a wide area manner. The proposed algorithm, upon detecting any voltage violation (both under- and/or over-voltages), employs organized multi-agent system (OMAS) in order to coordinate the employment of reactive power devices in returning voltage magnitudes of all buses to the acceptable range and steady behaviour. In order to achieve high benefits of power system response, each agent takes advantage of a predictive scheme, which is based on the corresponding bus voltage trend. By this predictive characteristic, each agent coordinates its command for remedial action with the prediction of bus voltage destination. Moreover, this predictive characteristic is extended to consider incoming remedial actions (or to compensate the latency in activation of previously decided remedial actions). These predictive characteristics lead to making a smooth waveform and reducing the number of needed remedial actions. The performance of the proposed scheme against different scenarios in Nordic32 test system is presented, where the results illustrate effectiveness and robustness of the proposed scheme.

1. Introduction

Wide area monitoring, protection, and control (WAMPAC) is a platform for control strategies, having a global management on power system disturbances with more effective contributions, if well-organized indeed. WAMPAC can prevent the spread of large disturbances by processing system-wide information gathered from all/selected local points. Indeed, WAMPAC became enabled when synchronized measurement technology (SMT) found its application in phasor measurement units (PMUs). These devices provide voltage and current phasor and frequency information, synchronized with high accuracy to a common time reference produced by a global positioning system. More key reasons for implementation of WAMPAC systems have been addressed in [1,2].

By employing wide area monitoring under conventional centralized control approach [3,4], although a pseudo real time data measurement gathered from dynamics of power system is created, the weakness of these schemes in maintaining resiliency in power system remains. Moreover, the traffic in data transferring to a unit control center and high dependency on this control center is additional problem of these approaches.

Besides, in recent years, a distributed control strategy named as multi-agent system (MAS) has been introduced by artificial intelligence researchers. By employing MAS, a complex problem is split to some easier sub-problems and each sub-problem is delegated to an agent; while agents of an MAS are in communication, cooperation, and coordination [2]. With the development and complement of the MAS theory, many power engineers have attempted to apply it to power system control schemes in recent years.

Hitherto, by employing MAS in the field of voltage control (mainly under-voltages), various schemes have been proposed. In [2], an MAS under WAMPAC framework has been introduced, in order to simulate the cooperation and coordination of agents in eliminating under-voltages against power system disturbances. In [5], by applying MAS in a small test system, an optimal control issue has been formulated and an index has been presented to provide coordination of tap changer transformers. In [6], an agent based algorithm for integrated volt/var control has been presented which provides distributed intelligence for smart grid. The voltage regulator and shunt capacitor controlled by intelligent agents collaborate to determine optimal setting for maintaining the system voltage profile and reducing the switching of shunt capacitors. In [7], an MAS-based scheme has been proposed to prevent long term voltage instability induced by cascading trips. In this scheme an optimal emergency control strategy has been derived based on sensitivity analysis. In [8], a multi-agent based hierarchical control has been presented, in order to maintain secure voltages in autonomous micro grid. In [9], a multi-agent receding horizon control (RHC) has been introduced to prevent voltage collapse in a multi-area power system; where each agent preserves its local information and communicates with its neighbours to find an optimal solution. Also, in [10], a

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novel multi-agent-based voltage control scheme has been presented, which dynamically adapts the settings of control devices (such as AVR of generators, on-load tap changers- OLTCs, and FACTS) to optimize operational objectives (such as maintain voltage stability, improve voltage profile, and reduce transmission power loss). In [11], an agent based distributed reactive power management scheme has been proposed to improve the voltage stability of energy distribution systems with distributed generation units. In [12], a multi-agent control system (MACS) has been proposed to eliminate the congestion of feeders and amend voltage violations by coordinating the operation of reactive power control sources and/or reconfiguring the distribution network. In [13], a multi-agent system based decentralized coordinated control scheme has been constructed to deal with the complex energy management problem of DGs. Finally, in [14] a secondary voltage regulation strategy based on multi-agent theory has been presented for improving the performance of secondary voltage control actions under different system operating states, where the concept of virtual control agency has been proposed to adapt the emergency dynamic control environment.

A brief comparison of the previously published methods and the one in this paper has been given in Table 1.

This paper follows the fundamental concepts of [2] in applying MAS for dynamic voltage control of power systems. But it innovates in proposing a voltage control scheme with the following novel features (rather than [2] and other schemes):

- Predictive, as it decides to take remedial actions according to:
  - ○ relying on the prediction of bus voltage destination via its trends in recovery of voltage magnitudes, whenever they are helpful (i.e., following a disturbance, there are bus voltage magnitudes, that after an under-shoot and/or over-shoot, return back to the permissible voltage limit; because of automatic actions of AVRs. Identification of these situations and relying on voltage trends for restoration of voltage magnitudes manages any request for remedial actions);
  - ○ notification of incoming remedial actions (i.e., at each time instant, there may be remedial actions to become activated now or in the future, upon the requests in the past. Identification of these actions, which are in the queue, and predicting their contributions on bus voltages, again, manages any request for remedial actions);
  - ○ double-sided in controlling voltage magnitudes, i.e. taking actions against over-voltages as well as under-voltages.
  - ○ efficient, as it is able to control voltages, dynamically, with lower number of actions, more effective and higher speed in achieving acceptable results, and more powerful in controlling against stressful disturbances.

The rest of this paper is structured as follows. In Section 2, the basic concepts, including MAS and dynamic voltage control, are described. The proposed approach is introduced in Section 3. The simulated power system and the results are explained and discussed in Section 4. Finally, at the end, conclusions are presented.

2. Basic concepts

In this section, the basic concepts of MAS and dynamic voltage control are described.

2.1. Multi-agent system (MAS)

Multi-agent systems are composed of devices with sensing, communicating, interacting, and computing elements, named as agents. The agents can be divided into two categories including Intelligent Agent (IA) and Reactive Agent (RA) [15]. IAs are systems with two important capabilities. First, they should contain appropriate software, capable of deciding for themselves what they need to do in order to satisfy their design objectives. Second, they should be capable of interacting with other IAs. The main features of an IA are communication, cooperation, coordination and negotiation. In power networks, the host computers in substations can behave as IAs and their collection in one of the common forms of organization (in this wok Holarchy organization was employed [16]) constitutes a multi-agent system. Actually, an MAS is a collection of IAs in companion with RAs; where the former ones cooperate and coordinate to solve a particular problem by controlling RAs, i.e. managing the actions assigned to RAs [17].

In this study, IAs are assumed to have the capability of receiving voltage phasors, analyzing received data, taking rational decisions, and sending commands to OLTCS, reactors, and capacitor banks. These are called Bus Agents (BAs). BAs can also make negotiations with other BAs, i.e. how each of agents tries to convince the others to help it in achieving its assigned goals. In this work, a scenario-based negotiation among BAs is applied, where a priority index is introduced and at each time the assigned value to each BA defines the priority of its commands, through which a clear and reliable agreement will be achieved in allocating and managing RAs.

Then, commands of BAs, for retaining power system integrity, are applied to each of RAs under its control. These commands, i.e. managing the positions of taps of OLTCs (with considering the inherent delays in tap changing [18]) and connectivity of reactors and capacitor banks, are delivered to and conducted by Tap Agents and Cap Agents, respectively. These agents are in the category of RAs.

The proposed organized multi-agent system (OMAS) is supposed to be built in companion with WAMPAC infrastructure, as shown in Fig. 1. Generally, there are phasor measurement units (PMUs) that measure

Table 1
Comparison of the reviewed schemes.

Schemes	Abilities					
	Reacting against sudden changes	Double-sided voltage control	Considering delays	Attempts to reduce remedial actions	Attempts to reduce settling time	Employing simple control devices
[2]	√	–	–	–	–	√
[5]	–	√	–	–	√	√
[6]	–	–	√	√	–	√
[7]	√	–	√	–	–	–
[8]	√	√	–	–	–	–
[9]	√	–	–	–	√	√
[10]	√	–	–	–	√	–
[11]	√	–	√	–	√	–
[12]	√	√	√	–	–	–
[13]	–	–	–	–	√	–
[14]	√	√	–	–	–	–
This paper	√	√	√	√	√	√

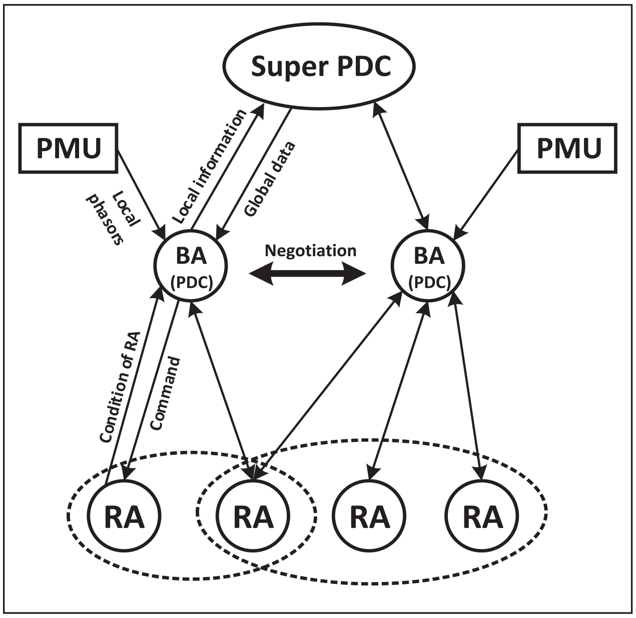

Fig. 1. Proposed interrelation of OMAS and WAMPAC.

and submit bus voltage phasors at a pre-defined frame rate to phasor data concentrators (local PDCs) which have the same role and position as BAs. The data gathered in this medium are analyzed by the associated BA, continuously, as well as those delivered to super PDC to be processed. Then, super PDC calculates those variables which need data from the whole network (in this work, sensitivity factors of bus voltages to the actions of reactive resources), and distributes the results back to all BAs. Details are explained in Section 3.

2.2. Dynamic voltage control

Voltage stability is an important issue in power system analysis. In this paper, a wide-area and dynamic voltage control strategy is proposed, where if a contingency happens in a network and any voltage phasor magnitude outgoes acceptable limits (i.e. $0.95\,\text{pu} \le V \le 1.05\,\text{pu}$), different BAs will take rational decisions after negotiating with other BAs. Final decisions will be interpreted by RAs to actions (i.e. tap changing in OLTCs or changing the connectivity of reactors and capacitor banks); with the hope that power system returns back to its normal steady condition. This procedure may be followed more than once in order to achieve the goal of voltage control.

On the basis of described concepts in this section and based on defined MAS framework in [2], the graphical structure of a BA unit and a RA unit, has been illustrated in Fig. 2.

3. The proposed scheme

Based on the data gathered in WAMPAC, directed by OMAS, and following the attributes presented in Section 2, the proposed algorithm is able to control power system voltages against disturbances such as sudden and heavy changes of loads (including load rejection or load injections) and outages of critical apparatuses (such as transmission lines, transformers and generators).

Steps of the proposed voltage control scheme, shown in Fig. 3, are as follows (improvements rather than [2] are highlighted):

Initializations

At the first step (S1), all buses in the network except for buses belonging to generators, are chosen as BAs.

In the second step (S2), RAs are allocated to BAs by two strategies, including:

- By sensitivity factors (i.e. dV/dQ for capacitor banks and reactors and dV/dTap for OLTCs), i.e. each BA possesses those RAs which show large sensitivity factors to the corresponding bus voltage.
- By the fact that an RA existing in the same substation of a BA is allocated to that BA.

It may happen that one RA is chosen by more than one BA, simultaneously. The third step (S3) determines common RAs between BAs.

Steps 1, 2 and 3 are followed for any topology of power system; and while the topology remains as it is, these steps need not to be repeated.

Identifying voltage violations

In the fourth step (S4), recorded bus voltage phasors by PMUs are delivered, continuously, to their corresponding BAs ($V_k[t]$ is the magnitude of the kth bus voltage phasor at time t). Then, in the fifth step (S5), each BA distinguishes what has happened to its associated bus voltage, whether it experiences under-voltage ($V_k < 0.95\,\text{pu}$) or over-voltage ($V_k > 1.05\,\text{pu}$). If any voltage phasor exits the permissible range (i.e. $0.95\,\text{pu} \le V \le 1.05\,\text{pu}$), OMAS will try to eliminate voltage violations and when all voltage phasors are within the permissible range, it returns back to step 4.

First predictive characteristic

As aforementioned, one of the predictive features of the proposed scheme is that each BA considers the trend and the destination of its associated bus voltage magnitude in deciding to request remedial actions.

In this regard, each BA applies a curve fitting (second order function in this work) upon voltage phasor samples. Then, either the rate of change (ramp trend) of this function or its final value (extrapolation trend) is distinguished (as illustrated in Fig. 4).

In the case of:

- under-voltages happened in the system, and increasing voltage trend (positive rate of change) or a voltage trend approaching to upper values than 0.95 pu; and/or
- over-voltages happened in the system, and decreasing voltage trend (negative rate of change) or advancing toward lower values than 1.05 pu,

any decision/command by that BA will be postponed until the next round. Otherwise, OMAS becomes ready to take rational decisions for that BA as well as the others.

This predictive based decision-making leads to a smooth/powerful performance and reduces the number of remedial actions (the results have been shown in Section 4).

Second predictive characteristic

In order to determine the amount of need of each BA to be assisted by RAs, another new and predictive feature of the proposed scheme is applied. This is including to compensate the effect of inherent latency in activation of OLTCs (i.e. Tap Agents) and/or Cap Agents. Practically, there may be Tap Agents (or Cap Agents) which have been previously asked for activation by their associated BAs, but as they have inherent latency, they will become active after a time delay (this delay has been reported as 2–10 s [18], and while by proposed mechanism, there are no significant differences in the results for different amounts of this delay [19], here, it has been chosen as 3 s).

Considering those incoming RAs, which are going to become active, and compensating their latency make OMAS to take more rational

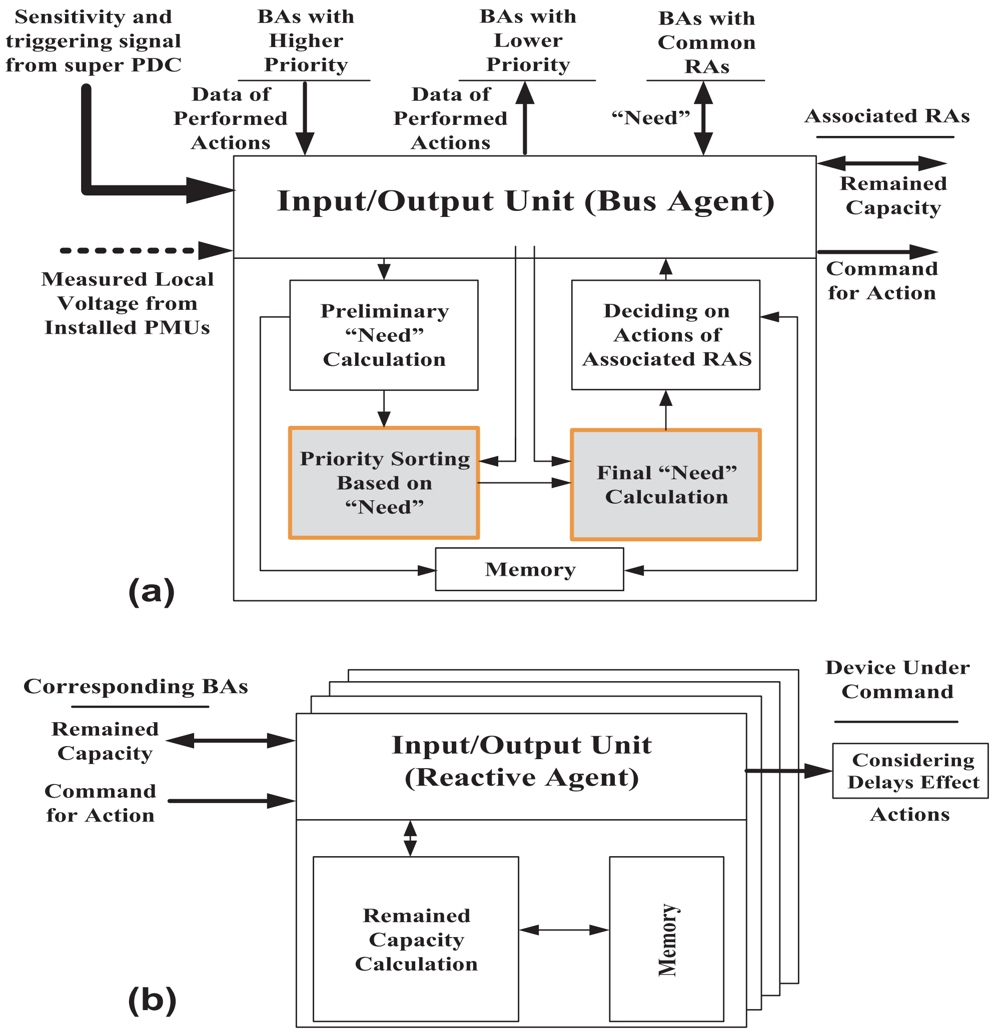

Fig. 2. The structure of Bus Agent (a) and Reactive Agent (b).

decisions and delivering requests for remedial actions at any time. This is another realistic and predictive attribute of the proposed algorithm (the results have been shown in Section 4).

To formulate this compensation function (CF), at any time, the contributions of all historical orders to RAs, which are going to become active later, are considered as follows:

$$CF_k[t] = \sum_{i=1}^{n} \frac{dV_k}{dQ_i} \times \Delta Q_i \times W_i + \sum_{j=1}^{m} \frac{dV_k}{dTap_j} \times \Delta Tap_j \times W_j \quad (1)$$

where CF_k is the compensation function for the kth BA, ΔQ is the amount of reactive power injection/rejection for one step change in position of Cap Agents, ΔTap is the quantity of changing in position of Tap Agents which is equal to one for one step change. Also, n and m are the number of Cap Agents and Tap Agents, respectively, selected as remedial actions and are stayed in queue. W_i and W_j may be valued as either:

- "one" only for those incoming RAs that are going to become activated now, at time t (the result is named CFA in Table 2), or
- "one" for all incoming RAs that are going to become activated now and in the future (the result is named CFB in Table 2).

Then, the amount of additive needed voltage to eliminate under-voltage and/or subtractive needed voltage to remove over-voltage conditions is calculated as:

$$\Delta V_k[t] = \begin{cases} 0.95 - V_k[t] - CF_k[t] & \text{if } V_k[t] < 0.95 \\ 1.05 - V_k[t] - CF_k[t] & \text{if } V_k[t] > 1.05 \end{cases} \quad (2)$$

where, obviously, ΔV_k is positive for uncompensated under-voltages and negative for uncompensated over-voltages.

Preparation for double-sided characteristic

Before passing to the next step, as a requirement of the third attribute of the proposed scheme, viz., double-sided control strategy, the inspection is done to find whether the whole power system is in under-voltage or over-voltage condition. The inspection is done by summing ΔV of all BAs in the system. This summation, named as ΣΔV, will represent under-voltage mode if it has positive value and its negative value shows over-voltage mode.

Now, the priority list is created in a descending order according to |ΔV|, for those BAs whose ΔV has the same polarity as ΣΔV. This priority list is the basis of the proposed scenario-based negotiation.

Scenario-based Negotiation

Now as the requirements for simulating the negotiation process among BAs are available, in the S7, determination of the final allocation of RAs to BAs is performed. In fact, the negotiation strategy is based on the priority list of BAs created in S6.

Allocation of RAs to BAs (from the one in the list with the highest priority), is found by applying the following index, which ascertains

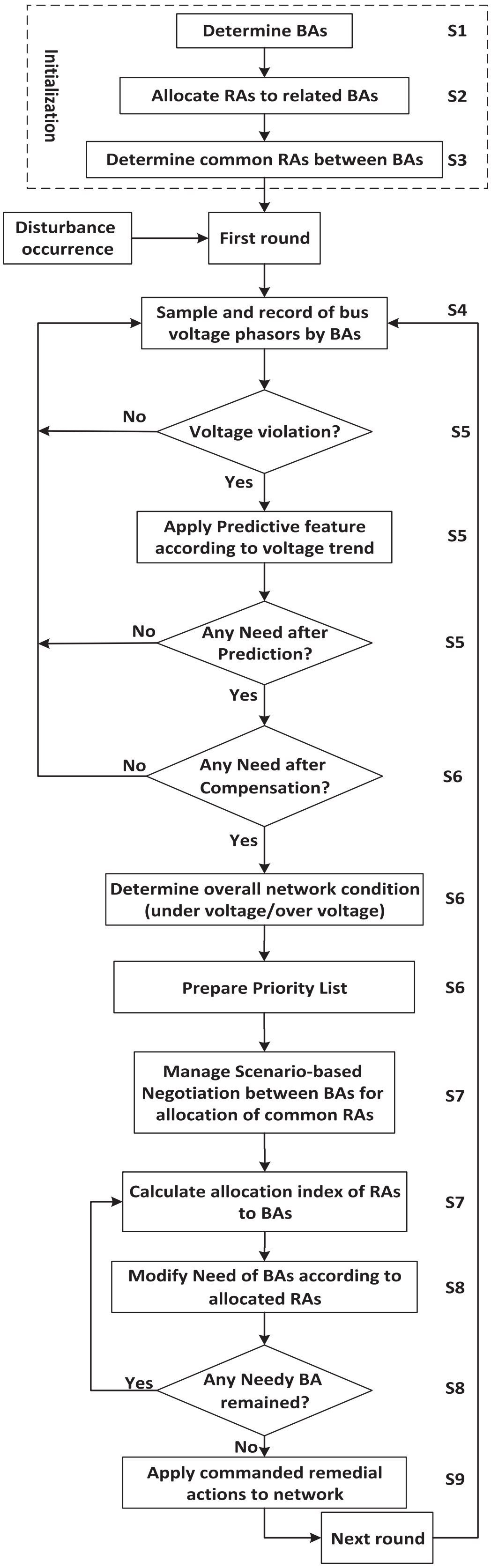

Fig. 3. The flowchart of the proposed voltage control scheme.

connection or release of more effective Cap Agents and raising or lowering Tap Agents with larger contributions to eliminate voltage violation from the BA under consideration:

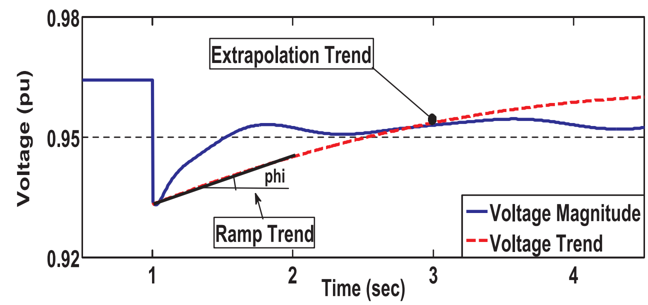

Fig. 4. Approaches for considering voltage trend.

$$Indx_{kj}[t] = \Delta RA_j \times Sen_{kj} \tag{3}$$

where

if $\sum \Delta V > 0$ and $\Delta V_k > 0$

$\Delta RA_j = remained\ cap.\ bank/connected\ reactor/tap\ increment$
$for\ positive\ Sen\ and\ tap\ decrement\ for\ negative\ Sen$

if $\sum \Delta V < 0$ and $\Delta V_k < 0$

$\Delta RA_j = connected\ cap.\ bank/remained\ reactor/tap\ decrement$
$for\ positive\ Sen\ and\ tap\ increment\ for\ negative\ Sen$

i.e. whenever BA senses under-voltage either remained capacitor banks should become connected or connected reactors should be released or taps in OLTCs should have increments for positive sensitivity factor and decrements for negative sensitivity factor; and vice versa for over-voltage cases. In the above relation, Sen_{kj} is the sensitivity factor of the voltage of the kth BA to the remedial action of the jth RA. RAs of a BA are also ranked in a descending order according to their $|dV[t]|$.

Now, in a successive manner, for the first of the BAs in the priority list, the allocated RAs are considered one-by-one, according to their ranking, until the voltage violation of that BA vanishes. It should be noted that the last RA in this operation may not be completely employed; and some of its capacity may remain for other BAs.

Obviously, the BA whose need is processed and provided will leave the priority list and those RAs which are completely employed in this process should be deleted from the list of allocation for other BAs.

Repetition for all BAs

In the eighth step (S8), before following the previous step for the second BA in the queue (and then for the others), the effects of actions assigned to RAs on the voltages of the remained BAs in the queue should be estimated. These estimations are considered in modification of the voltage violations, i.e. needs of the remained BAs in the priority list, as follows:

$$\Delta V_{final-k}[t] = \Delta V_k[t] - \sum_{j\in Q} Indx_{kj}[t] \tag{4}$$

where Q is the list of employed RAs by the former BAs in the priority list.

Then, the algorithm returns to the previous step and this repetition should be done up to when no BA remains in the list.

Operation of RAs

In the last step (S9), assigned commands to the selected RAs are applied to the network.

Here, the first round is finished and the next round starts one sec. later, from S4 until voltage violations in all BAs are removed. Here, it's necessary to mention that described mechanism, are employed just for those BAs which have experienced voltage violation with the same polarity as overall network condition, and not all BAs.

Table 2
Results of different techniques applied by the proposed OMAS for voltage control.

Scenarios	First predictive characteristic						Second predictive characteristic		Number of remedial actions	Settling time (s)
	Ramp trend			Extrapolation trend			CFA	CFA		
	Linear	Exp.	2nd order	Linear	Exp.	2nd order				
Case 1	–	–	–	–	–	–	–	–	80	36
Case 2	✓	–	–	–	–	–	–	–	49	12
Case 3	–	✓	–	–	–	–	–	–	47	12
Case 4	–	–	✓	–	–	–	–	–	39	11
Case 5	–	–	–	✓	–	–	–	–	55	10
Case 6	–	–	–	–	✓	–	–	–	52	10
Case 7	–	–	–	–	–	✓	–	–	47	11
Case 8	–	–	–	–	–	–	✓	–	61	14
Case 9	–	–	–	–	–	–	–	✓	56	13
Case 10	–	–	–	–	–	✓	–	✓	40	8
Case 11	–	–	✓	–	–	–	–	✓	34	8
Proposed case										

4. Simulation and results

In order to simulate the proposed scheme in a large scale power system, Nordic32 power system [20] was chosen, which is shown in Fig. 5. This network is composed of 20 generators, 9 capacitor banks, 2 reactor banks, 37 transformers, 20 generation buses and 41 non-generation buses. There are two transformer couples, where each of them is considered as a single RA. Therefore, OMAS is composed of 41 BAs and 46 RAs (11 Cap Agents and 35 Tap Agents). Generation units are equipped with governor, AVR and OEL control systems and loads are dependent on voltage and frequency changes.

The proposed scheme has been tested on the test system in DIgSILENT environment under various scenarios and its efficiency has been proven according to the obtained results, while some of them are presented in this paper. Also, OMAS has been implemented by several DPLs (DIgSILENT Programming Language) in DIgSILENT software.

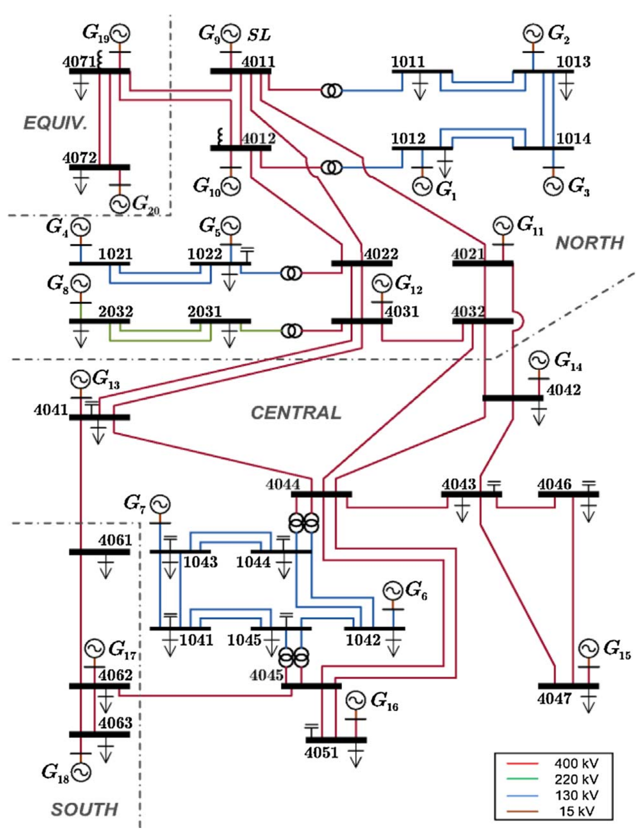

Fig. 5. The test system (Nordic32).

Here, in order to investigate on the efficiency of the proposed scheme, five different scenarios are analyzed as follows:

- The effect of predictive characteristics of the proposed method on the total performance of OMAS.
- The effect of time delays upon performance of proposed OMAS.
- The performance of OMAS against load variations.
- The performance of proposed OMAS against cascaded contingencies.
- The performance of proposed OMAS in comparison with the other approaches.

4.1. The predictive characteristics of proposed OMAS

The important aspects of the proposed method correspond to making decisions on remedial actions based on prediction of voltage trajectory (for whether remedial actions are required or not) as well as considering the incoming activations of RAs (where as much they satisfy the voltage requirements, remedial actions are ignored).

Here, in order to evaluate the efficacy of the proposed solution for the test system, 1043 transformer at the 5th s was disconnected from the network and the consumed active and reactive powers in all loads were increased by 5% at the 6th s Table 2 compares the results of the proposed scheme with different options. It can be seen that in this case OMAS without any predictive attributes (the first row in Table 2) has the largest number of remedial actions with the largest settling time. This happens due to injection of more than enough reactive power by some BAs. On the other hand, employing predictive features, i.e. considering voltage trends and compensation function, even individually, has enhanced the performance of OMAS as given in Table 2. Finally, the proposed OMAS by employing both of predictive attributes has provided the most optimal solution i.e. the least number of actions with the smallest settling time and providing smoother trajectories for the magnitude of voltage phasors, as shown in Fig. 6 and Table 2.

In this figure, the performance of the proposed OMAS has been also compared with the case that no RAs (neither Cap nor Tap agents) were employed and the controllers in the test system were only AVRs of generators (named as minimal control), which has not been able to turn voltages back to permissible limits.

4.2. The effect of time delays upon proposed OMAS

The actual performance of proposed OMAS based voltage control scheme might introduce some delays because of negotiation delays, computation delays, and delays of implementing the actions in network. Fig. 7 shows the sum of delays between the detection of voltage

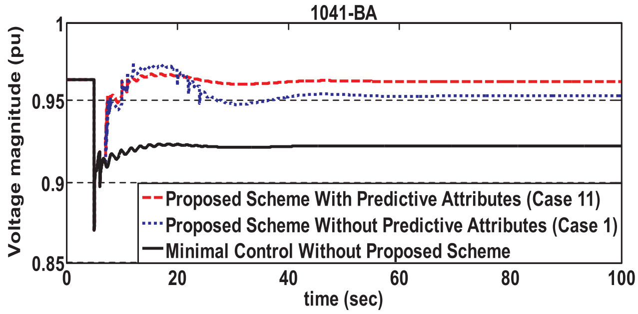

Fig. 6. The effect of predictive characteristics of OMAS.

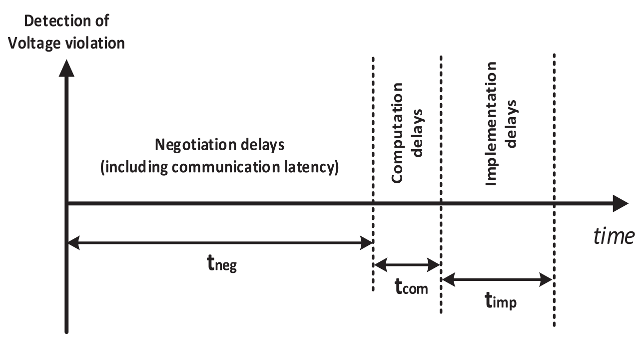

Fig. 7. The time line of delays in OMAS performance.

violation and the actual implementation of the remedial actions on a time scale [21]. The total delays can be defined as follows:

$$T_{delay} = t_{neg} + t_{com} + t_{imp} \quad (5)$$

where T_{delay} is the sum of delays is system, t_{neg} is the required time by the agents for negotiation (including communication latency), t_{com} is the time for computation processes, and t_{imp} is the time of implementing the remedial actions after decision making (including inherent latency in activation of OLTCs).

Knowing that moving toward long term voltage instability occurs slowly, it can be expected that the presence of the mentioned latencies has no significant contribution on the response, except that the contribution starts with delay.

As an example, the consumed active and reactive powers in all loads were increased by 5% and 40% at the 4th s, respectively. The results by considering T_{delay} as 5 and 10 s by the proposed OMAS for the described scenario have been shown in Fig. 8 (for two BAs, only). For comparison, the response without considering delay and by minimal control are shown, as well. It can be seen that with the presence of delays, the remedial actions can successfully make the system to return back to within the limits. The total number of remedial actions by the proposed OMAS without delay, with 5 s delay, and with 10 s delay are 47, 56, and 60, and the settling times are 8 s, 13 s, and 18 s, respectively.

4.3. The OMAS performance against load variations

In the second scenario, the performance of the proposed OMAS in eliminating voltage violations as a consequence of load variations was investigated. The results, in confronting with 50% increase of consumed reactive power in all loads at the 5th s, have been compared with the previous attempt of this laboratory [2] in Fig. 9. It can be seen (shown for one BA while totally 4 BAs experienced under-voltage), while the proposed MAS in [2] cannot restore the magnitude of voltage phasor of the mentioned BA, by employing the proposed scheme (with predictive attributes) voltage violation has easily been eliminated. Also, a part of the time line of the first round of applying the proposed scheme, in this case, has been illustrated in Fig. 10.

Moreover, the proposed MAS in [2] is unable of solving over-voltage

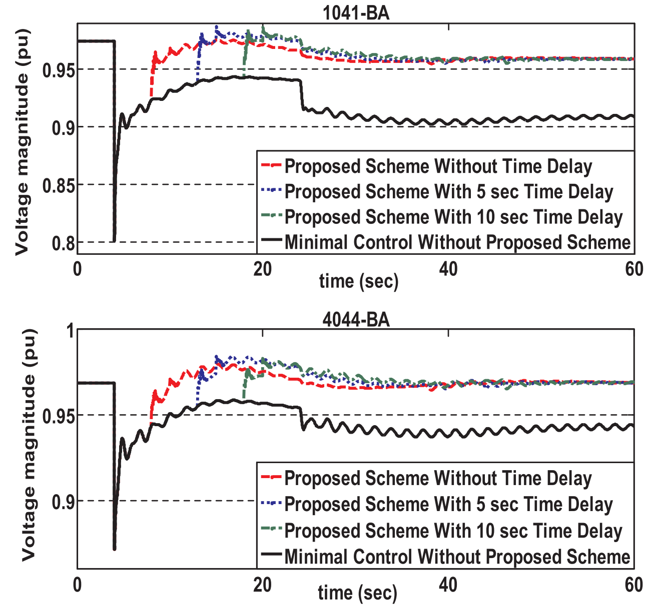

Fig. 8. The effect of time delays upon proposed OMAS.

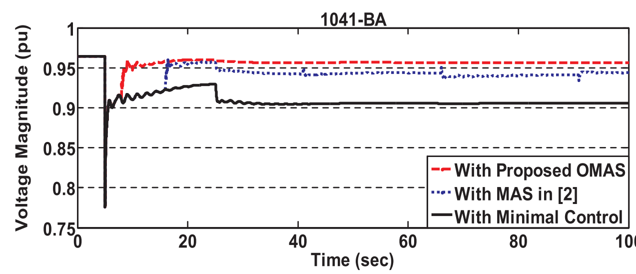

Fig. 9. The performance of OMAS against under-voltages.

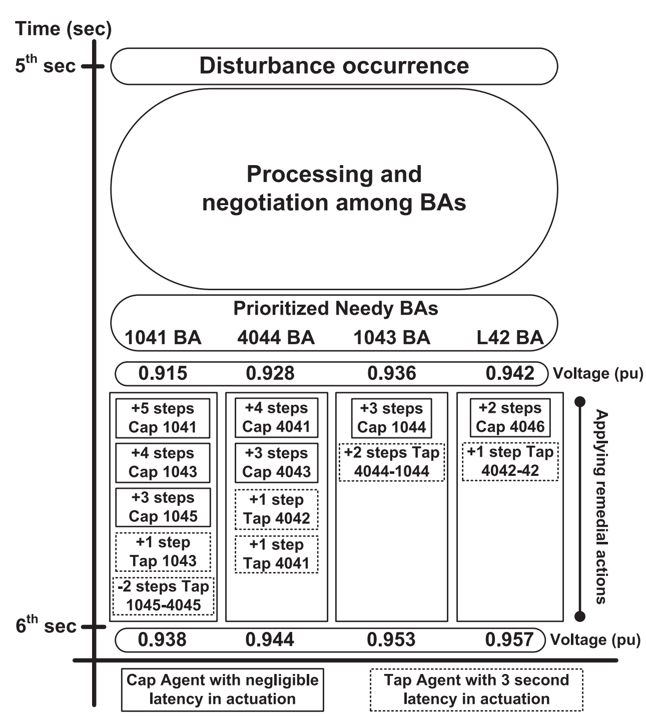

Fig. 10. The time line of applying the first round of the proposed scheme.

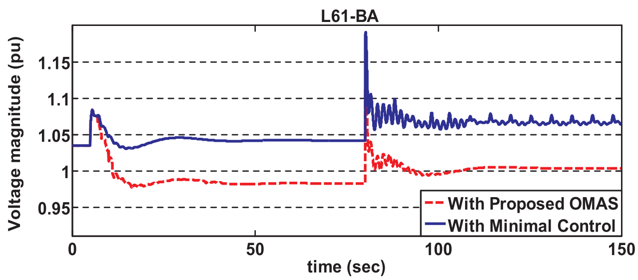

Fig. 11. The performance of OMAS against over-voltages.

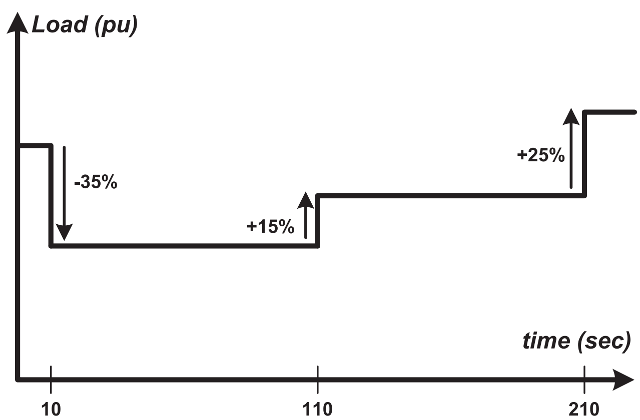

Fig. 12. Load curve used for all loads in the test system.

problems, because it has been just designed for under-voltage modes. But with the proposed OMAS, as shown in Fig. 11 (which are the results of simulation for one of BAs in the test system upon decreasing 10% of the consumed active and reactive power at the 5th s and again decreasing 100% of the consumed reactive power at the 80th s), the controlling attempt is successful (while totally 3 BAs experienced over-voltage). The same figure illustrates the result of disabling all RAs and relying only on AVRs, where it fails to show an acceptable control.

For further inspection on the abilities of the proposed scheme, abrupt load changes, as shown in Fig. 12, was used for all loads of the test system. Fig. 13 shows the success of the proposed OMAS in controlling voltage phasors (for two BAs are presented, while totally 7 BAs

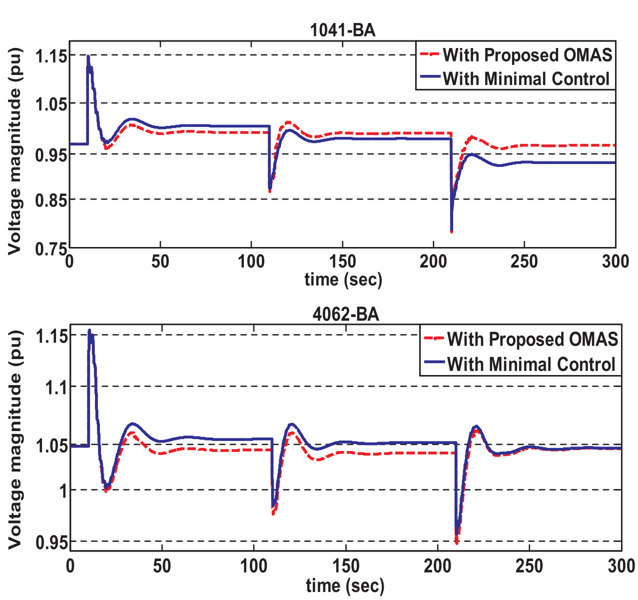

Fig. 13. Voltage phasors of two BAs in confronting with load variations according to the load curve of Fig. 12.

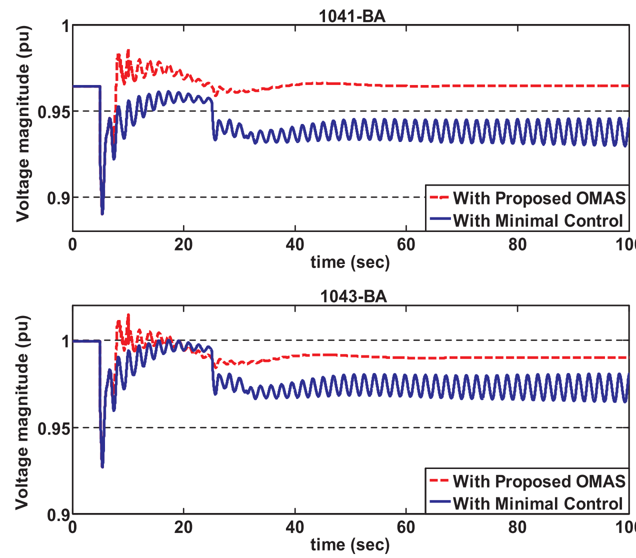

Fig. 14. The efficiency of OMAS against voltage oscillation.

experienced voltage violation) against this load variation. These results show that the proposed control scheme has an appropriate and powerful performance as it can keep voltage magnitudes within allowable range, even after any sudden change in power system.

4.4. *The efficiency of proposed OMAS against cascaded contingencies*

In this investigation, two cases were considered. First, outage of 4032–4044 line at the 5th s was simulated with 2.2% increase of all loads at same time. As shown in Fig. 14, the system experienced voltage oscillation when no RAs were in service (minimal control), while the proposed controller has eliminated voltage oscillations in all BAs (two of them are shown here while totally 6 BAs experienced under-voltage with oscillation). In the second case, 4032–4044 line of the test system was disconnected from the network at the 5th second and the consumed reactive and active power of all loads were increased at the 7th s as much as 4%. In this condition, as depicted in Fig. 15, without OMAS, power system will collapse. By employing the proposed OMAS, the voltage of all BAs remained within the permissible limit as shown in Fig. 16.

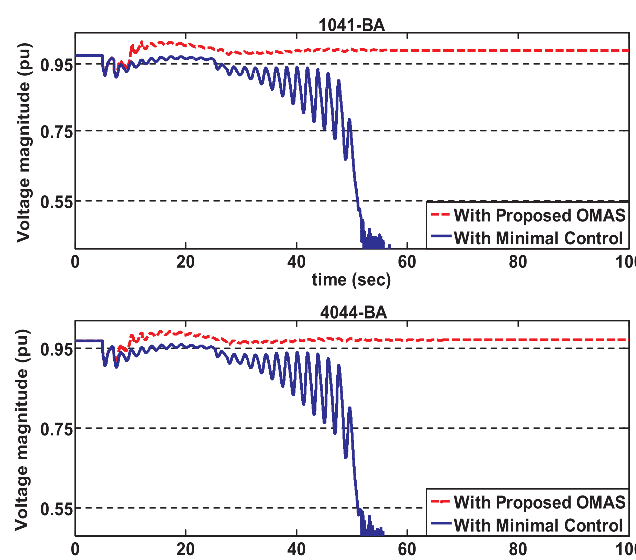

Fig. 15. The performance of OMAS against voltage collapse.

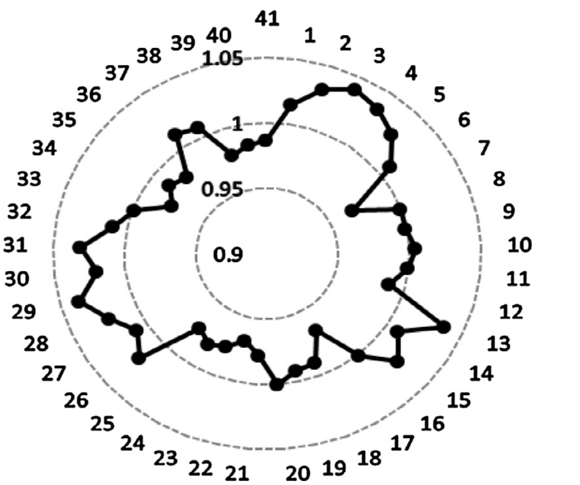

Fig. 16. The voltage magnitudes of all BAs by applying the proposed scheme against voltage collapse scenario.

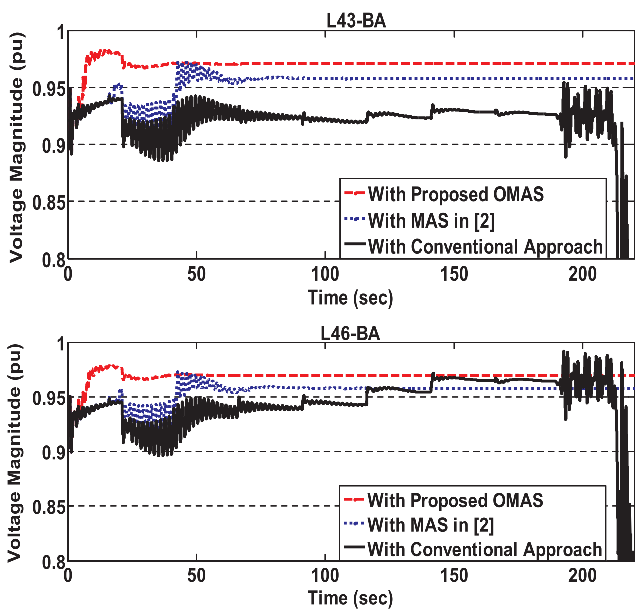

Fig. 17. The improvements of proposed scheme against [2].

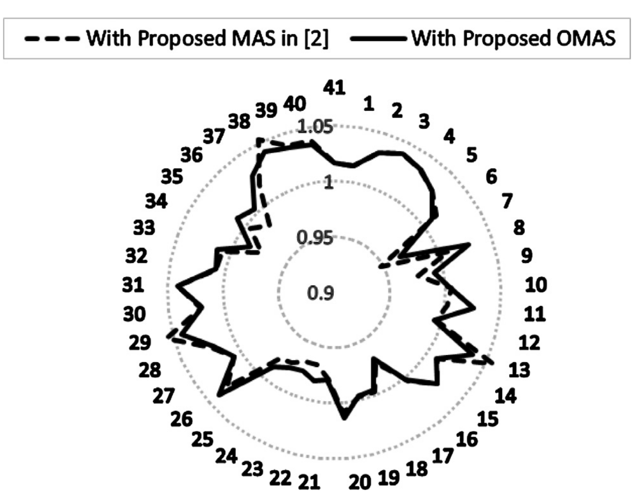

Fig. 18. The voltage magnitudes of all BAs by applying the proposed OMAS and proposed MAS scheme in [2].

4.5. The performance of proposed OMAS in comparison with other schemes

Finally, and after presenting some aspects of the performance of the proposed OMAS, in order to show the improvements of OMAS with respect to the proposed MAS in [2], their simulation results after disconnection of 4032–4044 line at the 1st s and increasing of the consumed active and reactive power in 1041 load at the 2nd s as large as 4% have been shown in Fig. 17. This figure illustrates that conventional control scheme (where all voltage control devices act locally and without coordination or cooperation)

has no success in this case and the proposed OMAS has more efficient and smooth performance rather than the proposed MAS in [2]; while both are successful in long-term control. On the other hand, the number of remedial actions by employing the proposed OMAS in this paper and the proposed MAS in [2] are 62 and 75, respectively. In addition, the settling times for them are 9 and 46 s (while the time delays were considered here and were not considered in [2]). Moreover, some of BAs experienced over-voltage by proposed scheme in [2], due to injection of more than enough reactive power by some BAs, while by employing proposed scheme in this paper, all BAs remain within allowable ranges as shown in Fig. 18. These results show the superiority and improvement in the proposed OMAS scheme in comparison with [2].

The reason behind the superiority of the proposed algorithm rather than [2] are the predictive features (i.e. considering voltage trend and compensating the latency of reactive power resources contributions in the process of decision-making for remedial actions against voltage violations), as well as shorter time between rounds, which lead to better response with smooth waveform, lesser remedial actions, and shorter settling time rather than [2]. Also this paper gives a double-sided scheme in controlling voltage magnitudes, i.e. taking actions against over-voltages as well as under-voltages in power system.

5. Conclusion

In this paper, a dynamic voltage control under WAMPAC framework has been presented. This scheme, proposed on the basis of organized multi-agent systems (OMAS), is able to eliminate voltage violations (under- or over-voltages) following disturbances in power system, even those leading to voltage oscillations and/or voltage collapse. The novelty of the proposed scheme is in its predictive attributes, i.e. considering voltage trend and compensating the latency of reactive power resources contributions in the process of decision-making for remedial actions against voltage violations. These characteristics have made the proposed scheme to be more efficient with less remedial actions and smaller settling time. Moreover, it proven that the remedial actions successfully implemented by the presence of various latencies without causing any significant deviation in the response. The performance of the presented scheme has been investigated on a test system, comprehensively, under various operating conditions and for different disturbances (load variations and contingencies). The results have shown the ability and superiority of the proposed algorithm in a wide-area and dynamic voltage control approach.

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