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Prevention of Voltage Instability by Adaptive Determination of Tap Position in OLTCs

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Abstract—**This paper introduces a robust and appropriate algorithm for dynamic voltage control by adaptive/predictive determination of tap position in OLTCs (according to their nonlinear behavior) for preventing voltage instability which may caused by them. The OLTCs can be destructive as much as their advantages, because they have not specified and linear characteristic (like capacitor banks) and it requires a predictive/adaptive manner for finding the appropriate and safe rate of changes of taps in OLTCs. To this end, an adaptive manner on the basis of sensitivity analysis is proposed in this paper. By employing this method, the appropriate changes in tap position of each OLTCs is determined at any time. The results of simulations in Nordic32 test system demonstrate effectiveness and robustness of the proposed scheme.**

Keywords- sensitivity analysis; voltage stability; on-load tap changer (OLTC); reactive power control; Dynamic voltage control.

I. INTRODUCTION

In recent years, power systems have been forced to squeeze the maximum possible electrical energy through existing networks due to different limitations in the composition of generation and transmission equipment. Hence, the power systems is operated closer to the stability limits. One of the major problems occurring from this condition, is increased probability of power system instability. Generally, there are two forms of instability in power systems: the instability due to loss of synchronism among synchronous machines and the instability from loss of voltage stability. The voltage instability is studied in this paper.

Voltage instability has been responsible for great blackouts in recent years [1]. As a definition, voltage stability is the ability of a power system to maintain steady and acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance [2], [3]. When there is voltage drop in one or several buses due to a disturbance such as a change in system condition due to fluctuation in loads, and outage of equipment, there is voltage instability in system. The main cause for a voltage instability in the power systems is the inadequacy in provision and transmission of demanded reactive powers.

To meet the increasing demands and/or after contingency occurrence in the network, the reactive power should be injected (by generators, capacitor banks or SVCs) and/or transferred (by OLTCs) in power system. If, voltage magnitude of a bus after injection of reactive power increased, the system has a voltage stability. In other wise, i.e. reduction of voltage magnitude of a bus after injection of reactive power, the system is said to experience voltage instability.

Voltage instability is a local phenomenon but its results may have a widespread impact. This phenomenon leads to reduction in voltage profile of system and it can have a cumulative effect, ultimately, leading to voltage collapse [2].

Based on time span, voltage stability can be classified as short-term voltage stability and long-term voltage stability. Short-term voltage stability involves dynamics of fast acting load components such as induction motors, electronically controlled loads, switched capacitor banks, and HVDC converters. The study period of these cases is in the order of several seconds [3]. Long-term voltage stability involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. The study period of these cases may extend to several or many minutes [3]. More descriptions and solutions for voltage instability have been addressed in [3-10].

The focus of this paper is on the long-term voltage stability, where the performance of OLTCs is more effective. In power system, under increased demands and/or contingency occurrence, the voltage magnitudes of some buses may drop and for maintaining voltage stability, the generation units try to produce more active and reactive power and transmission lines should transfer more power. On the other hand, generation units and transmission lines have specified limitations in generation and transfer of active and reactive power. Under this condition, the OLTCs also try to transfer reactive power from strong buses. Thus, the interferences between OLTCs performance and generators and/or transmission lines reactive power limitations may lead to voltage instability, if the OLTCs actions remain uncontrolled [3], [4].

Therefore, an appropriate mechanism is needed to prevent voltage instability due to OLTCs destructive performances. Up to now, different papers have dealt with this problem. In [11], a nonlinear dynamic model of the OLTC, impedance loads, and decoupled reactive power-voltage relations has been employed to reconstruct the voltage collapse phenomenon. This paper identifies the smallest equilibrium from an invariant set and establishes the existence and stability of this equilibrium. In [12], an equivalency procedure to perform both modal and nodal reduction has been described which accounts for load areas under OLTC transformers in medium- to long-term dynamic studies. This paper acknowledged by comparing, both in steady-state and dynamic conditions, voltage and current, and therefore active and reactive power, at common specific buses in the original and equivalent system. In [13], the effect of on-load tap changers on the maximum power transfer limits and the voltage stability have been discussed both analytically and numerically. In [14], an approach, based on sensitivity analysis, is presented for identifying critical transformers and employing manual settings for them to avoid voltage instability conditions, which may occur under peak load conditions. In [15], the role of automatic and non-automatic OLTCs for emergency and preventive voltage stability control has been reviewed. Also, it has discussed how tap-blocking and tap-reversing of bulk power delivery OLTC transformers can prevent an approaching voltage collapse, as well as the problems and limitations of these countermeasures and the advantages gained by tap-reversing. Also in [16], a secondary voltage intelligent method has developed based on fuzzy expert system, where in order to augment voltage stability and security, the OLTCs has been controlled in an intelligent way.

Most of the proposed schemes in the field of controlling the effects of OLTCs on voltage stability are based on single step change in tap position of OLTCs at each stage, and with a large time delay between each change (in the order of several minutes).

Here, the main interest of this paper is on the dynamic voltage control by coordination of reactive power resources, with the focus on long-term voltage stability and adaptive control of OLTCs performance with the intention of preventing voltage instability and/or voltage collapse due to interferences between OLTCs performance and reactive power limitations of generation units. The proposed scheme has an adaptive/predictive determination of tap position in OLTCs at each stage on the basis of sensitivity analysis, for maintaining voltage security in power system. The number of selected steps in any change of tap position is not equal to one at each stage, necessarily. Also, the time delay between each stage change is so small (in the order of second), in contrast to the conventional methods.

The rest of this article has been structured as follows. In section II, the methodology and the proposed scheme are explained. The simulation and numerical results are described and discussed in Section III. Finally, conclusions are represented.

II. METHODOLOGY

The performance of on-load tap changer transformers in power system can be useful and effective, if well coordinated and controlled, indeed. One of the problems which leads to long-term voltage instability and collapse in power system is the incorrect performance of OLTCs in network. In more details, after a disturbance occurrence in power system (e.g. increase of demands or outage of equipment), the generators increase their produced power and transmission lines are forced to transfer more power, but both of generation units and transmission lines have limitations in generated or transferred active and reactive power. In the event that, the generated or transferred power of these devices exceeds from their limitations, the system goes toward instability. Furthermore, OLTCs can have influence on transferring of reactive power from strong points (buses with enough/high voltage magnitude) to weak points (buses with low voltage magnitude) in network. Hence, the interferences between OLTCs performance and reactive power limitations of generation units or transmission lines may lead to voltage instability or collapse in emergency condition. In this process, those OLTC transformers which are directly connected to the terminals of generators (as shown in Fig. 1), have the most impact on voltage instability phenomenon, because these transformers are the only path for the generated reactive power by increasing tap values in OLTCs. Any conflict between the generated reactive power and reactive power transferability of OLTCs will lead to voltage instability occurrence.

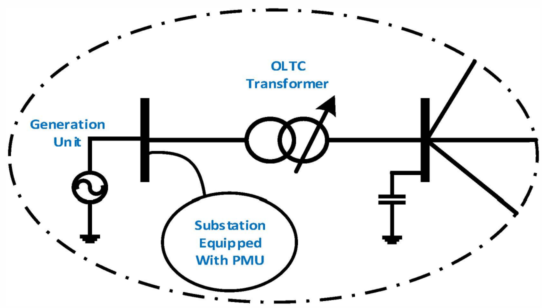

Figure 1. Construction of an OLTC connected to generation unit.

As mentioned, the focus of this paper is on the effect of OLTCs destructive performance on the reactive power limitations of generation units. On the basis of mentioned concepts, the proposed scheme shown in Fig. 2 is described in the following.

It is assumed that the information of voltage phasors of all busbars is available continuously, via phasor measurement units (PMUs) installed in all substations. Now, if voltage magnitude of any busbar outgoes from the permissible range (i.e. 0.95 pu<V<1.05 pu), a voltage violation has happened. The quantity of voltage violation is calculated as follow:

$$dV_k[t]=\begin{cases}0.95\text{-}V_k[t] & \text{if: } V_k[t]<0.95\\ 1.05\text{-}V_k[t] & \text{if: } V_k[t]>1.05\end{cases} \tag{1}$$

where $dV_k[t]$ is the amount of voltage violation in the k^{th} busbar at time t and $V_k[t]$ is the voltage magnitude of that busbar at the same time.

Then, according to the magnitude of dV, busbars are sorted. Also, for determining the amount of effectiveness of reactive power resources (including reactors and capacitor banks, and OLTC transformers) on those busbars that have voltage violation, a sensitivity analysis is done and reactive power devices are sorted according to their effectiveness (where dV/dQ and dV/dTap are the amount of effectiveness/sensitivity factor for reactors/capacitor banks, and OLTCs respectively).

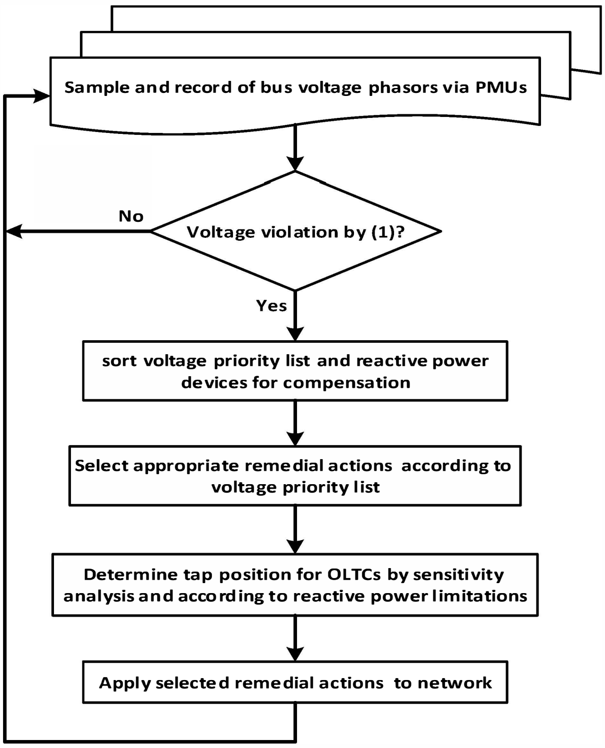

Figure 2. The flowchart of the proposed algorithm.

In the following, according to the sorted busbars and reactive power devices, for the busbar with highest priority (highest voltage violation), the reactive power resources are chosen for compensation process by considering two limitations in each stage. First is a physical limitation in each device to change from current position which defined as n_{max} and n_{min} for reactors, capacitor banks, and OLTC transformers. Second is the limitation in voltage magnitude of each busbars which will be appeared after change in the reactive power resources. The voltage magnitude of each busbar after any change in reactive power devices should be within permissible range (i.e. 0.95 pu<V<1.05 pu), which is estimated by sensitivity analysis as follows:

$$V_k[n+1]=V_k[n]+\Delta V_k[n] \tag{2}$$

where $V_k[n]$ is the voltage magnitude in the k^{th} busbar under current position of reactive power devices (i.e. n^{th} position), $V_k[n+1]$ is the amount of next coming voltage magnitude in the k^{th} busbar and $\Delta V_k[n]$ is the amount of change in voltage magnitude of the k^{th} busbar due to one step change in position of reactive power devices which is calculated from sensitivity analysis. Then, for the next change in position of reactive power devices, by applying $V_k[n+1]$, the new amount for sensitivity factor is calculated. Thus, by entering these new obtained parameters (i.e. $V_k[n+1]$ and $\Delta V_k[n+1]$) into (2), the next-coming voltages are estimated. This process continues until voltage magnitude exceeds from allowable range.

For preventing voltage instability due to tap changing of OLTCs, an additional limit has been considered in this paper. This limit is considered against the interferences between OLTCs performance and reactive power limitations of generation units. In this process, first, the maximum reactive power capacity of generators from the reactive capability curve [17], which can be analytically represented based on the maximum field voltage (E^{max}) [9], is calculated as follows:

$$Q_g^{max}=\frac{VE^{max}}{X_d}\cos(\delta-\theta)-V^2\left(\frac{\sin^2(\delta-\theta)}{X_q}+\frac{\cos^2(\delta-\theta)}{X_d}\right) \tag{3}$$

where E^{max} is the maximum field voltage of generator, V is the terminal voltage magnitude of associated generator, X_q and X_d are represented the quadrature and direct axis reactances of generator, ϴ is the phase angle of terminal voltage of generator, and δ is the rotor angle of generator in a synchronously rotating reference frame.

By calculating the amount of maximum reactive power capacity of generators at each stage by (3), and also, by calculating the quantity of transferred reactive power by OLTC transformers, connected to generator busbars at each stage, an additional constraint is considered for preventing voltage instability, via comparing these two parameters. To this end, according to equivalent circuit of OLTCs shown in Fig. 4, and according to the directions of reactive powers flowed into this equivalent circuit as shown in Fig. 5, the related limit is defined. So that, the transferred reactive power into OLTCs (Q_{in}) at each stage and after any change in tap position of OLTC, should be less than maximum reactive power capacity of related generator (Q_g^{max}). Here, a sensitivity analysis is done for estimating the amount of next coming voltage magnitudes after changes in tap position of OLTCs. Through this scenario, an adaptive/predictive determination for tap position of OLTCs is done by considering appropriate limits, in order to prevent voltage instability.

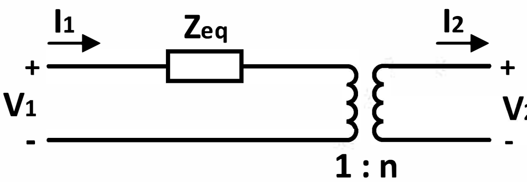

Figure 3. Circuit representation of transformer with tap changer in secondary side.

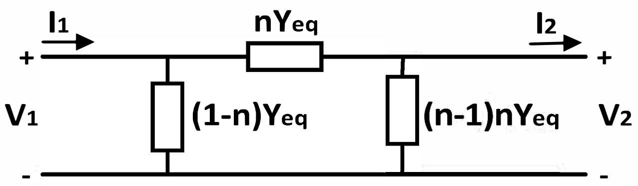

Figure 4. Equivalent circuit for an OLTC transformer with real tap ratio.

In the circuit of Fig. 4, n is a real tap ratio which defined as $n=n_1/n_2$, also Y_{eq} is series admittance of transformer which defined as $Y_{eq}=1/Z_{eq}=1/R+j\omega L$.

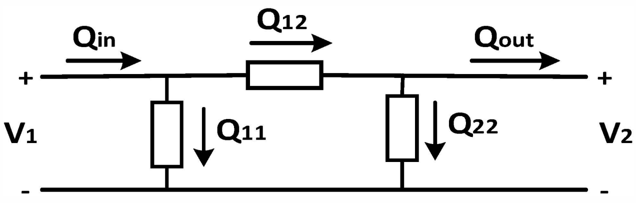

Figure 5. Flow of reactive power in OLTC's Equivalent circuit.

The amounts of reactive powers in Fig. 5 are calculated as follows:

$$Q_{12}=Q_{22}+Q_{loss}+Q_{out} \tag{4}$$

$$Q_{22}=(n^2-n)Y_{eq}^{*}\left|V_2\right|^2 \tag{5}$$

$$Q_{loss}=nY_{eq}^{*}\left|V_1-V_2\right|^2 \tag{6}$$

$$Q_{in}=Q_{11}+Q_{12} \tag{7}$$

$$Q_{11}=(1-n)Y_{eq}^{*}\left|V_1\right|^2 \tag{8}$$

The above variables are calculated by applying $V_k[n+1]$ from (2) and, then, the following inequality is checked to find whether, the change in tap position will be safe or not:

$$Q_g^{max} \geq Q_{in} \geq Q_g^{min} \tag{9}$$

Finally, appropriate remedial actions are selected to eliminate voltage violation by considering strict limits for preventing voltage instability due to interferences between OLTCs performance and reactive power limitations of generation units, and applied to network and repeated, while voltage violations exist.

III. Simulation and Results

In order to apply the proposed algorithm in a large scale power system, modified Nordic32 test system [18] was chosen, which is demonstrated in Fig. 6. This network is composed of 20 generators, 9 capacitor banks, 2 reactors, 37 OLTC transformers, 20 generation busbars and 41 non-generation busbars. The proposed scheme was tested on this network in DIgSILENT software and its efficiency and reliability has been proven according to the obtained results, where some of them are presented here.

In this section, to evaluate the efficiency of the proposed solution in determination of tap position (with the intention of preventing voltage instability and/or voltage collapse), the consumed reactive power in 1041 load, has been increased as much as 60% at the fifth second. Under this scenario, the voltage magnitude of 1041 busbar experiences the under-voltage condition, as shown in Fig. 7. According to sensitivity analysis, the 1043 OLTC transformer has the highest influence on 1041 busbar while 1041 capacitor bank is placed in the next priority for reactive power injection. The current tap position of 1043 transformer is on -2 position (corresponding to reduction of secondary voltage) and maximum reactive power capacity of g7 generator (connected to 1043 busbar via 1043 OLTC) is 170 MVAR, by (3). The results of analysis before and after contingency occurrence have been depicted in TABLE I and TABLE II, respectively. The, sensitivity factor in these tables demonstrates the rate of change in voltage magnitude of 1041 busbar due to one step incremental change in tap position of 1043 OLTC transformer.

As seen in the first row of TABLE I and II, after contingency, the input reactive power in transformer (or output reactive power from generator) has increased from 35.2 to 120 MVAR and sensitivity value is positive. This means that tap position can be increased one step further.

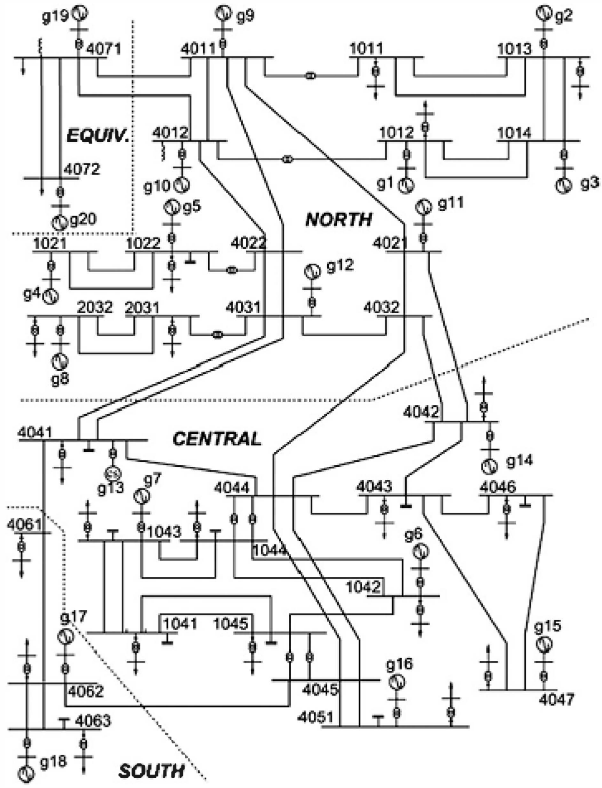

Figure 6. One line diagram of the Nordic32 test system.

TABLE I. Reactive power values of 1043 OLTC according to Fig. 5, before contingency

Tap position	Sensitivity factor	Q_{in} (MVAR)	Q_{11} (MVAR)	Q_{12} (MVAR)	Q_{loss} (MVAR)	Q_{22} (MVAR)	Q_{out} (MVAR)
-2	+0.008	+35.2	-2666.8	+2702	+56.35	+2610.7	+34.95

TABLE II. Reactive power values of 1043 OLTC according to Fig. 5, after contingency and under different tap positions

Tap position	Sensitivity factor	Q_{in} (MVAR)	Q_{11} (MVAR)	Q_{12} (MVAR)	Q_{loss} (MVAR)	Q_{22} (MVAR)	Q_{out} (MVAR)
-2	+0.0087	+120	-2666.6	+2786.6	+60	+2606.9	+119.7
-1	+0.0082	+143.1	-1333.1	+1476.2	+16.6	+1316.9	+142.7
0	+0.0082	+167.7	0	+167.7	+0.5	0	+167.2
+1	0	+170	+1309.4	-1139.4	+8.5	-1317.4	+169.5
+2	0	+170	+2566.3	-2396.3	+42.3	-2608.1	+169.5

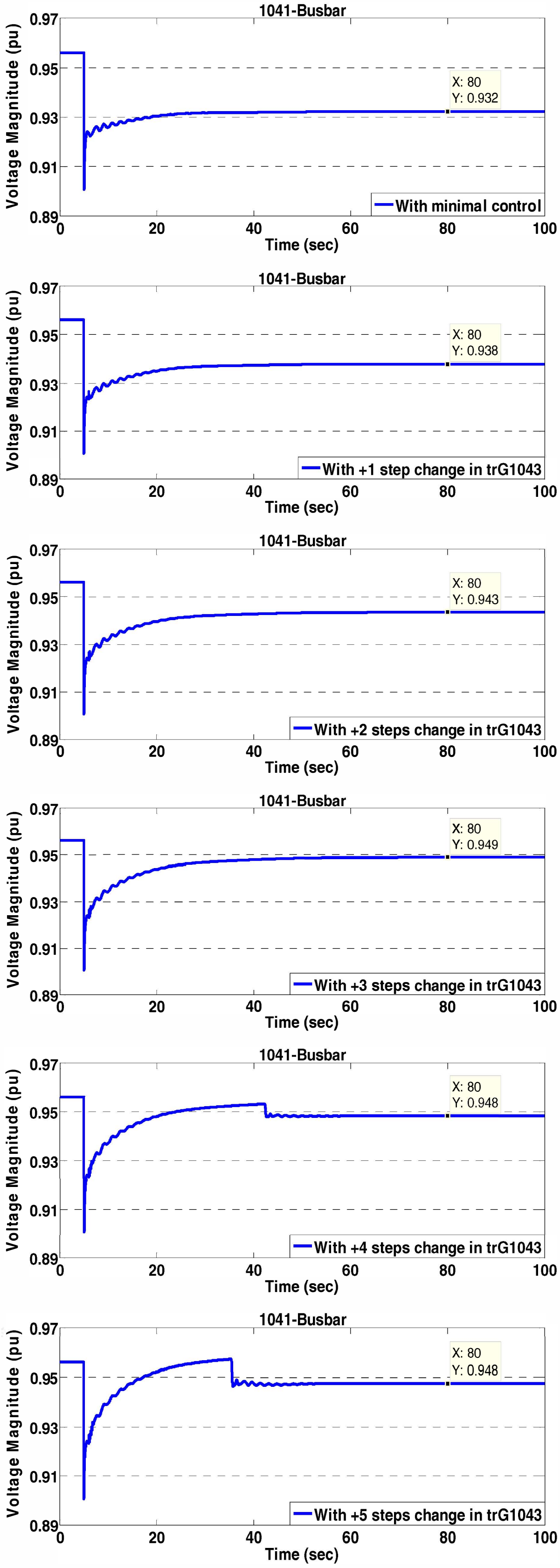

Figure 7. Trends of voltage magnitude in 1041 busbar under different changes in tap positions of 1043 OLTC transformer.

The results for next the steps (the second and third rows of TABLE II) show that sensitivity values are still positive as the input reactive power has not reached to its limitation, so another change in tap position is possible. But, the sensitivity value will become zero (or negative) as the input reactive power reaches to its limitation. This condition happens at +1 position of the tap, i.e. the possible rate in tap changing is equal to +3 steps. After this point, the sensitivity will be zero for the next changes, and input reactive power for transformer will remain at 170 MVAR (according to the maximum reactive power capacity of the related generator). It means that any force for increment of secondary voltage by increasing the tap of this OLTC is incredible and increasing tap position just leads to voltage instability and even voltage collapse.

The obtained results, shown in Fig.7 acknowledge the evaluated results in TABLE II, where it was found that +3 steps change in tap position of 1043 transformer is appropriate and more changes lead to voltage instability. Now the result for +3 steps change in 1043 tap changer in addition of using from the next reactive power device in priority list (i.e. 1041 capacitor bank), has been depicted in Fig. 8, where +3 steps change in tap position of 1043 transformer plus +3 steps change in 1041 capacitor bank lead to elimination of voltage violation in 1041 busbar, completely.

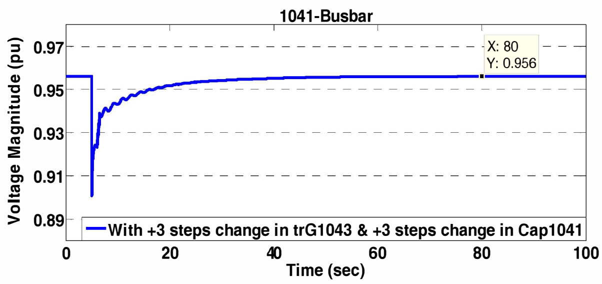

Figure 8. Trend of voltage magnitude in 1041 busbar by proposed scheme.

Here, to have a more evaluation on the proposed algorithm, another investigation was performed, where the consumed reactive power in all loads was increased as much as 40% at the fifth second. In this scenario, as shown in Fig. 9, three types of control scheme, have been employed. Case I, shows the results of employing the proposed scheme with all defined limitations (especially limitation of OLTC defined in (9)). As seen, with this algorithm voltage violation has been removed perfectly. Case II, demonstrates the results for employing the proposed scheme without the defined limitation in (9). So, between the performance of OLTC transformers and reactive power limitation in generators may occur some conflicts. As observed in Fig. 9, by employing this case, voltage collapse will occur. This issue reveals the effectiveness and necessity of applying the limitation defined by (9). Finally in Case III, the obtained result from employing minimal control (i.e. without using OLTCs and/or capacitor banks and just taking the advantages of generator's AVR) has been illustrated. Through this case, the under-voltage has not been eliminated, though voltage stability has been provided (although out of permissible range). This result illustrates the measure of importance of OLTCs performance on voltage stability and the requirement for an appropriate control scheme to coordinate them.

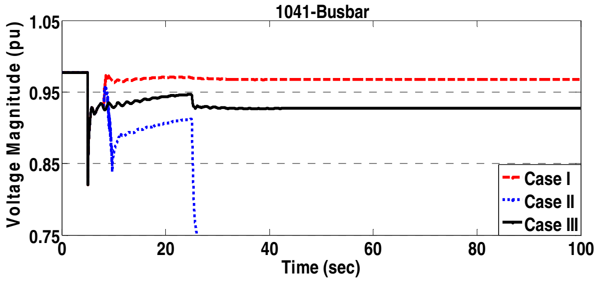

Figure 9. The evaluation of different schemes in 1041 busbar.

IV. CONCLUSION

In this paper, a dynamic voltage control scheme has been introduced with the application of sensitivity analysis. The focus of this paper was on the long-term voltage instability which may cause from interferences between OLTC transformers performance and the maximum reactive power limitation of generation units. To this end, through adaptive coordination of reactive power resources (such as OLTCs, reactors and capacitor banks), and also, predictive determination of OLTC's tap position based on sensitivity factors, an appropriate and secure voltage control (i.e. voltage stability and profile) is presented. By employing the proposed scheme, the rate of safe and effective changes in tap position of OLTC transformers are predictable in advance (to prevent voltage instability). The achieved results have shown the robustness and effectiveness of the proposed scheme in dynamic voltage control.

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