Secondary Voltage Control of a Multi-region Power System

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Secondary Voltage Control of a Multi-region Power System

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Abstract— **This paper presents schemes to perform secondary voltage control on the IEEE 39 bus system. The power system simulation and analyses are performed using DIgSILENT software. The tertiary voltage control is applied based on power system optimization process. The secondary voltage control is applied on the simulated system by three different schemes: scheme 1 is using a built-in function in DIgSILENT (station control facility), scheme 2 is establishing a new control model in the software application and scheme 3 is integrating DIgSILENT and MATLAB applications. A comparison between system performance using those three different schemes under different operating conditions is presented. The comparison shows that schemes 2 and 3 are identical and achieved better performance than the first scheme in terms of total power losses and voltage deviation index. A graphical theory algorithm is applied for power system partitioning and sensitivity analysis is used in pilot buses selection which proved their effectiveness through results.**

Keywords—**Secondary Voltage Control, Tertiary Voltage Control, Droop Analysis, DIgSILENT Power Factory, System Partitioning and Pilot Buses Selection.**

I. INTRODUCTION

The basic concept of smart grid is to have a good planning for different power system operation conditions to support system control, improve power quality and security as well as reducing the energy consumption and costs [1].

Voltage instability has been studied by many researchers and Engineers, it is considered as one of the main reasons that leads to power system insecurity which may drive to black or brown outages. Voltage instability phenomena can simply be described as the inability of bus voltage to return to its original value or acceptable value when the system is subjected to a disturbance [2].

Power system voltage control is mainly consisting of three main hierarchal levels which are [3, 4]:
i) Automatic voltage regulator (AVR) level: which is mainly directed to control the PV bus voltage magnitude, its time margin varies between milli seconds and 10 seconds
ii) Secondary voltage control level: which is mainly directed to control the voltage magnitude of PQ buses. The control is applied to the most sensitive bus to the reactive power variations in a region which is called pilot bus, its time margin of execution ranges from 10 mins to 25 mins.
iii) Tertiary voltage control level: which is an optimal load flow process to set the optimal values of each pilot bus. The process is applied every 30 mins, 45 mins or 60 mins depending on the setting of the power system operator.

In [2], the authors applied secondary voltage control on IEEE 14 bus system and considered it as a single region power system without taking into account the tertiary voltage control results. In this research the secondary voltage control will be applied to a multi-region power system considering tertiary voltage control level.

To apply secondary voltage control in a power system, two important steps are required which are system partitioning and pilot buses selection [6], [7]. In this paper, A technique was used for system partitioning based on [8]. The pilot buses selection was made using sensitivity analysis for each partition.

The system was simulated in DIgSILENT power Factory and three different methods were proposed to apply secondary voltage on the simulated model. The first method is to use the station control function with droop analysis which is a built-in function in the software, the second method is to establish conventional secondary voltage control scheme in the software application and the third method is to establish the secondary voltage control scheme in MATLAB / SIMULINK and integrate the two software applications.

The paper is organized as follows section II includes the power system description, section III illustrates how the system divided into regions and how pilot buses were selected, section IV discusses the idea of tertiary voltage control while section V illustrates how secondary voltage control was applied by different methods in the software applications. Section VI presents the simulation results and section VII summarizes the main conclusions.

II. SYSTEM DESCRIPTION

Fig. 1 (a) shows the simulated IEEE 39 bus system [9]. The simulated system consists of 39 buses (29 PQ buses and 10 PV buses), 10 generators and 46 transmission lines. Each generator is equipped with an IEEE Type 1 excitation system (AVR model IEEE T1) as shown in Fig. 1 (b) [10], and IEEE standard steam governor and turbine as shown in Fig. 1 (c) [11]. In our study, it is assumed that all the generators have the same types of AVRs and governors. .
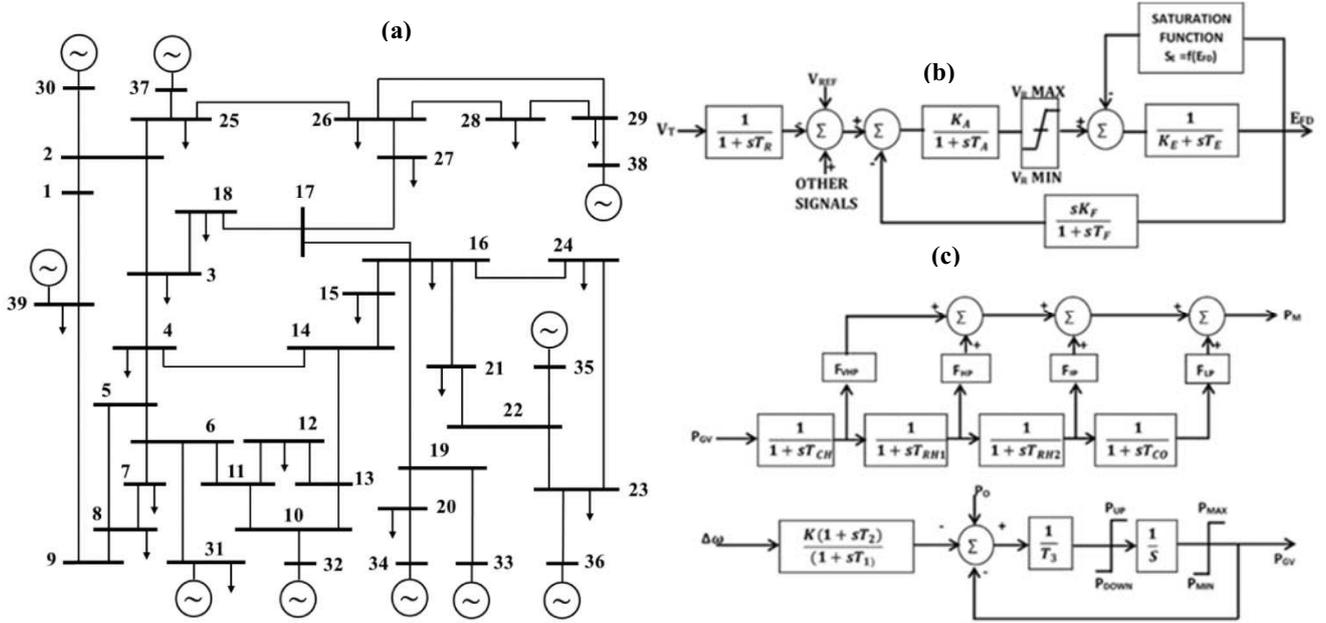
Fig. 1. (a) IEEE 39 bus system [9], (b) IEEE Type 1 excitation system AVR model [10] and (c) Steam governor and turbine model [11].

III. SYSTEM PARTITIONING AND PILOT BUSES SELECTION

To apply secondary voltage control, system partitioning should be applied to the grid then pilot buses should be selected.

A. Power system partitioning

The problem in dividing the grid into regions required to implement secondary voltage control mainly lies on the dependence of these areas with power system operation condition and the way where the electrical power grid upgrades. In general, it is better to reduce the coupling between the control areas to avoid the dynamic interaction between closed loops and reactive power exchange between regions.

Many researchers proposed different techniques for system partitioning, based on [6] the comparison between those techniques indicated that graph theory has overall better evaluation in terms of power system performance in base case and other operating conditions.

The graph theory solution to the partitioning problem by finding the partition matrix P, whose i^{th} column has the graph buses that belong to the ith partition. This partition matrix minimizes the objective function (1),

$$F = \sum_{B_i} \sum_{B_j} S_{ij} \tag{1}$$

Where S_{ij} is the apparent power between bus number i and bus number j which belongs to different partitions (it represents the weights of the lines cut by partitions)

The partitioning results is constrained by a condition that each region should at least include one generator (Reactive power source) to inject or absorb reactive power to control the voltage of the buses in the region.

After applying this method in the IEEE 39 bus system, it was concluded that the system can be divided into 6 areas as illustrated in Table I to achieve minimum objective function which stated in (1).

B. Pilot Buses selection

Secondary voltage control will be applied to the system in steps using a linear model. To describe the relation between voltage variations and power variations, different ways can be used such as:

1. Fast decoupled load flow solution where sensitivity matrix which relates voltage and reactive power variations is made equal to the negative nodal admittance matrix of the global system.
2. A more detailed model considers the active power flows in the electric network but neglects the effect of active power changes on voltage magnitudes, and this approach is the base of this research as illustrated in (2).
3. The exact model which considers the effect of incremental variations of active and reactive powers.

TABLE I. BUSES IN EACH REGION

Region ID	Buses in the region
1	1, 39
2	2, 3, 25, 30, 37
3	4, 5, 7, 8, 9, 6, 31, 11, 10, 32, 13, 12
4	27, 38, 28, 29, 26
5	33, 34, 20, 19, 15, 16, 21, 22, 35, 17, 18
6	23, 24, 36

$$\begin{bmatrix} S_{GG} & S_{GL} \\ S_{LG} & S_{LL} \end{bmatrix} \begin{bmatrix} \Delta V_G \\ \Delta V_L \end{bmatrix} = \begin{bmatrix} \Delta Q_G \\ \Delta Q_L \end{bmatrix} \tag{2}$$

Where ΔV_G, $\Delta V_L, \Delta Q_G$ and ΔQ_L are the change of PV bus voltage, the change of load bus voltage, the change of generated reactive power and the change of load reactive power respectively. the relation between voltage variation and reactive power variation are represented in S_{GG}, $S_{GL,}$ S_{LG} and S_{LL} submatrices.

From (2), it is found that

$$\Delta V_L = A \Delta Q_L + B \Delta V_G \tag{3}$$

In (3), the inverse of S_{LL} submatrix is A. The negative multiplication between inverse of S_{LL} submatrix and S_{LG} submatrix is B .

The control will be applied to a certain load bus in each region. This load bus is called pilot bus which has the most sensitive voltage variation with respect to reactive power variation.

$$\Delta V_P = M\Delta V_L \qquad (4)$$

M is a 0-1 matrix with rank ($n_P \times n_L$) to indicate which load buses are pilot buses, n_P is the number of pilot buses while n_L is the number of load buses in the system.

In this paper, the pilot buses were selected in each region by calculating the sensitivity matrix of the system and the load bus with the highest sensitivity factor $\frac{\partial V}{\partial Q}$ in each control area was selected to be a pilot bus as shown in Table II [6, 7].

TABLE II. SYSTEM PILOT BUSES

Region ID	Pilot Bus
1	Bus 1
2	Bus 3
3	Bus 4
4	Bus 27
5	Bus 16
6	Bus 24

IV. TERTIARY VOLTAGE CONTROL

Tertiary voltage control (TerVC) is responsible for changing the setting point of the pilot bus voltages to implement secondary voltage control (SecVC) based on optimal load flow process as shown in Fig. 2.
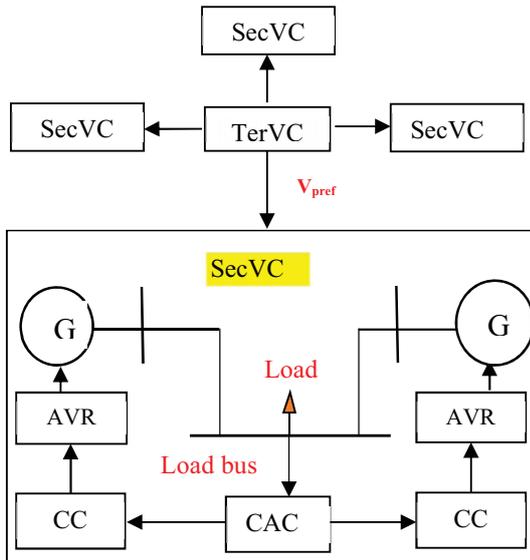
Fig. 2. Tertiary and Secondary Voltage Control Idea [2].

The optimal load flow is applied at different operating conditions based on the following description:

> Objective Function: Minimization of total active power losses or load shedding or generation cost or maximum reactive power reserve.
> Variables: Buses Voltage (magnitude and angle) and Generators active and reactive power
> Constraints: The optimization process is subjected to the following conditions:
> - Load Flow equations
> $$\sum PG - \sum PD - \sum PLoss = 0 \qquad (5)$$
> $$\sum QG - \sum QD - \sum QLoss = 0 \qquad (6)$$
> - Generating limits for each generator
> $$PG_{min} \le PG \le PG_{max} \qquad (7)$$
> $$QG_{min} \le QG \le QG_{max} \qquad (8)$$
> - Bus voltage magnitude level limits
> $$Vb_{min} \le Vb \le Vb_{max} \qquad (9)$$
> - Each Line loading thermal limit
> $$Pline \le Pline_{max} \qquad (10)$$

The objective function may include more than one objective as minimizing active power losses in addition to maximizing reactive power reserve, in this case the program applies normalization theory to reach optimal values that is acceptable for both objectives. In this paper the objective function is selected to be minimization of total active power losses.

In (9), the maximum and minimum voltage values differs from one operating condition to another, during the base case the minimum and maximum limits should be 95 % and 105% of the rated bus voltage magnitude respectively while during contingency (generator outage or line outage) the limits should be 90% and 110% of the rated bus voltage magnitude respectively.

V. SECONDARY VOLTAGE CONTROL TECHNIQUES

This paper presents three schemes to apply the secondary voltage control in DIgSILENT software. The first scheme depends on the station control function and droop analysis which are built-in functions in the program while the second scheme is to establish the conventional secondary voltage scheme in the DIgSILENT application and the third scheme is to establish the same conventional control of scheme 2 but in MATLAB / SIMULINK then integrate the two software applications.

A. Built-in station control function

A station controller is mainly a reactive power controller for one or more generators which will keep the voltage at a specific or automatically determined busbar at the given set point. In this paper this function was used to implement SecVC by applying the control in the pilot buses of each region and the set point was selected based on tertiary voltage control results. The built-in control scheme is shown in Fig. 3 and modeled in (11).

Reactive power control is important in any generating station to minimize circulating current but still allow good reactive support to the grid during different conditions. Reactive power droop controller assumes an impedance between the generator and the grid which creates a voltage- regulating point beyond the generator output and into the step-up transformer. With reactive droop, a small percentage of error is added to the input of the AVR measuring circuit that results in a very small change

in field voltage and, then, a change in generator terminal voltage takes place and leads to change in load voltage.
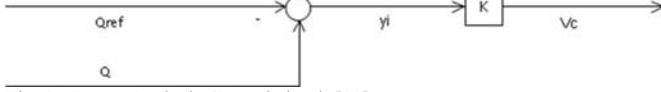

Fig. 3. Droop Analysis Control circuit [12].

$$V_c = V_{tref} + K(Q_{ref} - Q_g) \qquad (11)$$

V_c is the input of the AVR in order to ask the generator to increase or decrease the reactive power output to support the pilot bus voltage. Q_g is the actual reactive power measured at generator terminals while Q_{ref} is the reactive power required from the generator based on the tertiary voltage control method. And K is calculated to achieve the reference voltage of the pilot bus based on the optimal load flow process results. As long as K increase the generator terminal voltage decrease in the normal operating conditions so a balance should be applied between the base case and other operating conditions.
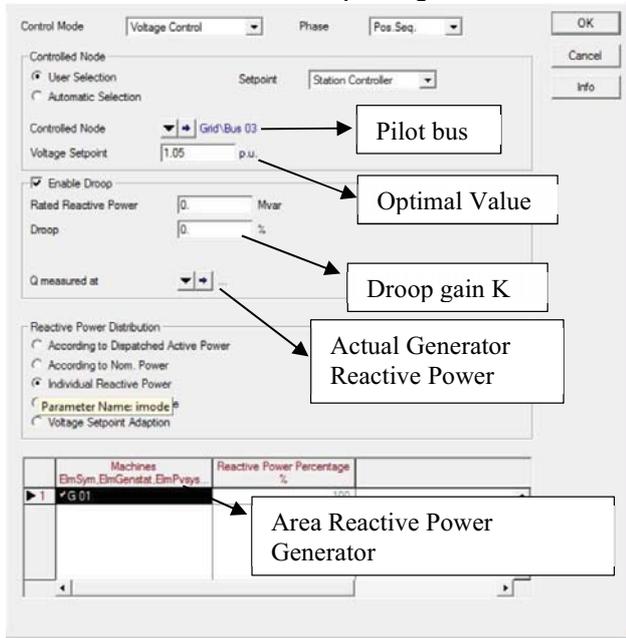

Fig. 4. Implementation of Station Control in DIgSILENT.

The droop gain K is calculated in this paper by the following formula,

$$K = \frac{V_{desired} - V_{actual}}{V_{actual}} \qquad (12)$$

where $V_{desired}$ is the optimal load voltage calculated in the tertiary control optimization process at a certain operation condition while V_{actual} is load voltage measured at the same operating condition without applying secondary voltage control.

B. Establishing conventional SecVC control scheme in DIgSILENT software application

As illustrated in [5] the control strategy in Fig. 2 and Fig. 5 achieves the secondary voltage control.

The circuit was built in DIgSILENT as shown in Fig. 6 by using standard macros facilities which are built-in functions inside the software library and the output of this scheme is an additional signal to the AVR reference.
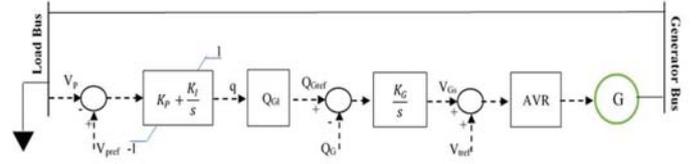

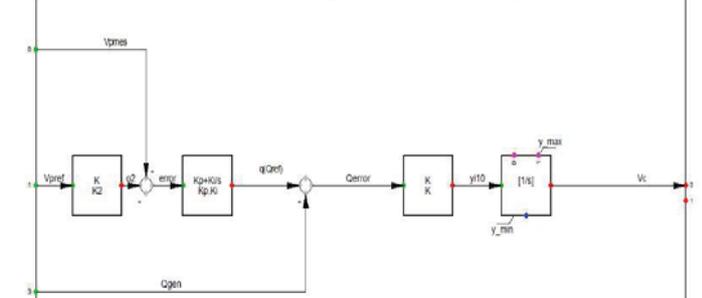Fig. 5. Conventional secondary voltage control scheme [12].

Fig. 6. Implementation of SecVC in DIgSILENT.

The following equations describe the control circuit:
i.   Central area control (CAC) equations

$$V_{pref} - V_p = \Delta V_p \qquad (13)$$

$$q = \left(K_p + \frac{K_I}{s}\right) \Delta V_p \qquad (14)$$

ii.   Unit cluster control (CC) equations

$$Q_{ref} = q * Q_{Gl} \qquad (15)$$

$$V_{GS} = \frac{K_G}{s}(Q_{ref} - Q_G) \qquad (16)$$

Where V_{pref} is pilot bus reference voltage calculated from tertiary voltage control, V_p is pilot bus actual voltage, ΔV_p is the voltage error, q is the control action, Q_{Gl} is the reactive power limit known from generator capability curve and V_{GS} is the additional signal to the AVR reference. The regulator integral gain K_G is calculated from the sensitivity matrix and is equivalent to $\frac{X_{TG} + X_{eq}}{T_G}$ where X_{TG} is generator transformer impedance while X_{eq} is line impedance and the time constant T_G is set to be 5 sec [2,13].

The proportional integral (PI) controller parameters K_p and K_I are calculated to achieve minimum error ΔV_p by applying the following mathematical minimization technique $\frac{d\Delta V_p}{ds} = 0$ through equations (13), (14), (15) and (16). The minimization result is shown in (17) and (18).

$$K_p = \frac{1}{X_{TG} Q_{GL}} \qquad (17)$$

$$K_I = \frac{1 + K_p Q_{GL} X_{eq}}{T_c Q_{Gl} X_{eq}} \qquad (18)$$

Tc is set to be 50 seconds in this research.

C. Integration between MATLAB and DIgSILENT

In this method the secondary voltage control in Fig. 6 is built in MATLAB/SIMULINK software and after that an integration between MATLAB and DIgSILENT took place. The interaction between the two applications occurs by using the following computer files [14-16]:
• Power Factory model (PFD)
• MATLAB data models in the form of m_files (m)
• MATLAB/SIMULINK model (mdl)

The m.files and MATLAB/SIMULINK models represent the model and algorithms of the external control circuit, and the Power Factory model represents the IEEE 39 bus system.

The same equations and parameters of the previous schemes are applied at this method to verify through results that the two schemes have the same performance.

Steps to integrate the two software applications:

i. Create a new composite frame in DIgSILENT
ii. Insert slots in the frame
iii. Define the slots (normally slot for the generator and slot(s) for the controller(s))
iv. Define the block of the controller by inserting the path for the m_File, variables names, parameters names and initial conditions
v. Create a Simulink file which includes the block diagram of the controller with the same variables' names and parameters names
vi. Create a common model and insert the parameter values of the controller
vii. Define the controller model to be the controller of the desired generator (either AVR or Governor or power system stabilizer or even another thing which was created (as secondary voltage controller)
viii. Define the event(s) (disturbance) in DIgSILENT and run the system from DIgSILENT

VI. SIMULATION RESULTS

In this research three disturbances are assumed to be occurred to the system to test the controllers' effectiveness and robustness. The first disturbance is generator contingency event after 5 secs from the starting of simulation, generator installed at bus 32 is tripped out of service. The second disturbance is line contingency, line connecting bus1 and bus 2 turned into out of service after 10 secs from the starting of simulation. The third disturbance is load increase, it is assumed that after 15 secs from starting the simulation, the load connected to bus 16 increase by 120%

A. Tertiary Voltage Control Results

After simulating the mentioned generator outage, line outage and load increasing disturbances at same time, an optimal power flow calculation took place to achieve minimum power loss if the system subjected to constraints (5), (6), (7), (8), (9) and (10). The results are shown in Table III.

B. Secondary Voltage Control Results

To achieve the optimal voltages in Table III secondary voltage control must be applied. Since there are 6 control regions in this system so there are 6 pilot buses, each pilot bus will include a secondary voltage control circuit. Each pilot bus will get reactive power support from a generator of its area as shown in the following Table IV.

1. Station Control Results

To apply SecVC a station control with droop analysis was applied to each pilot bus to reach optimal voltage calculated in the tertiary voltage control. The optimal voltage is set to be the reference voltage of the station controller and the droop gain was calculated for each station controller based on (12) as illustrated in Table V.

TABLE III. OPTIMAL POWER FLOW RESULTS AFTER THE THREE DISTURBANCES

Bus Number	Optimal Voltage
Bus 01	1.040298
Bus 02	1.01947
Bus 03	0.9856234
Bus 04	0.9639521
Bus 05	0.9641609
Bus 06	0.9672685
Bus 07	0.9588586
Bus 08	0.9591426
Bus 09	1.018759
Bus 10	0.9593053
Bus 11	0.9607259
Bus 12	0.9443328
Bus 13	0.9577222
Bus 14	0.9579342
Bus 15	0.9670427
Bus 16	0.9949633
Bus 17	0.9938081
Bus 18	0.9888048
Bus 19	1.032123
Bus 20	0.9804902
Bus 21	1.000287
Bus 22	1.030728
Bus 23	1.024531
Bus 24	1.000151
Bus 25	1.040892
Bus 26	1.022658
Bus 27	1.002238
Bus 28	1.028535
Bus 29	1.033538
Bus 30	1.0475
Bus 31	0.982
Bus 32	0.896547
Bus 33	0.9972
Bus 34	1.0123
Bus 35	1.0493
Bus 36	1.0635
Bus 37	1.0278
Bus 38	1.0265
Bus 39	1.040452

TABLE IV. PILOT BUSES SUPPORTIVE GENERATORS

Pilot Bus Number	Supportive Generator
Bus 01	Generator installed at Bus 39
Bus 03	Generator installed at Bus 37
Bus 04	Generator installed at Bus 31
Bus 16	Generator installed at Bus 35
Bus 24	Generator installed at Bus 36
Bus 27	Generator installed at Bus 38

TABLE V. DROOP GAIN IN EACH REGION

Pilot Bus Number	Droop gain
Bus 01	3%
Bus 03	1%
Bus 04	0.5%
Bus 16	2%
Bus 24	5%
Bus 27	1.5%

The results in Fig. 7 show good performance but with a small steady state error between 1% and 2% from achieving the optimal (reference) values of each pilot bus. It takes near 35 seconds for the system to reach steady state value (20 seconds after last disturbance). Fig.8 shows the supportive generators reactive power responses to enable each pilot bus to reach the

value shown in Fig.7. Fig.9 shows that all the load buses voltage magnitudes achieved values near optimal ones with small steady state error when station control technique was applied.
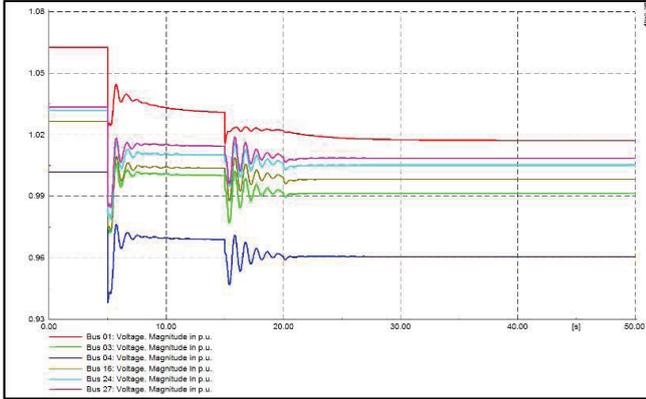

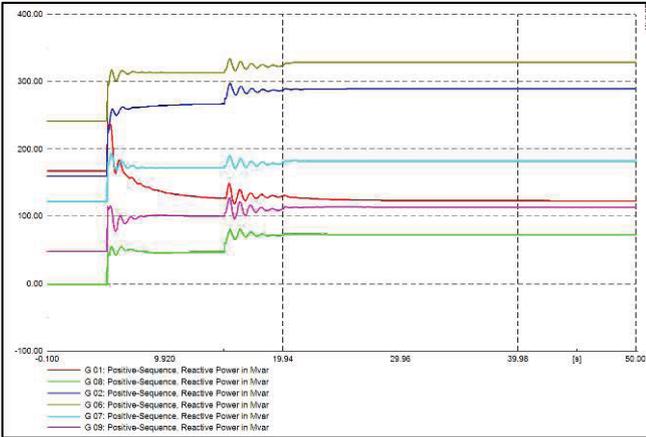Fig. 7. Pilot Bus Voltages response when station control applied to the system

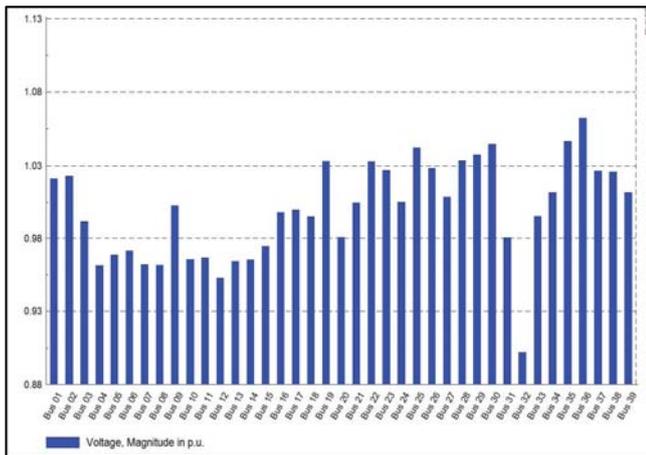Fig.8. Reactive power responses when station control applied to the system

Fig. 9. Grid buses Voltage when station control applied to the system

2. Building SecVC in DIgSILENT scheme

In this method a PI controller was used for each region to enable each pilot bus through reactive power support to reach its optimal voltage magnitude. The values of K_p and K_I in each controller are calculated based on (17) and (18) and shown in Table VI. The other parameters in the SecVC were calculated based on the power system data.

TABLE VI. PI PARAMETERS OF EACH CONTROL REGION

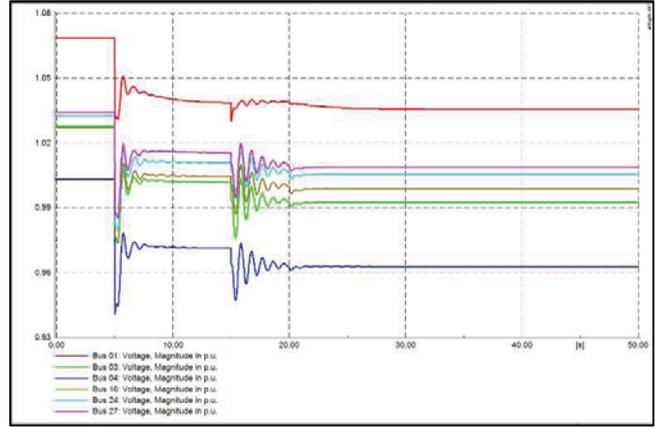| Region Number	K_p	K_I
1	1.23	0.34
2	2.2	1.51
3	1.82	0.96
4	1.45	0.27
5	1.78	1.26
6	2.57	1.47

Fig. 10. Pilot buses Voltage responses when SecVC circuits was built and applied in DIgSILENT.

Fig. 10 shows excellent performance with zero steady state error due to the presence of an integrator in each control area. It takes near 30 seconds to reach steady state values (15 seconds after last disturbance). Fig. 11 shows the reactive power required from supportive generators to allow pilot buses to reach optimal values and Fig. 12 ensure that by achieving optimal values in pilot buses, all buses will behave optimally.
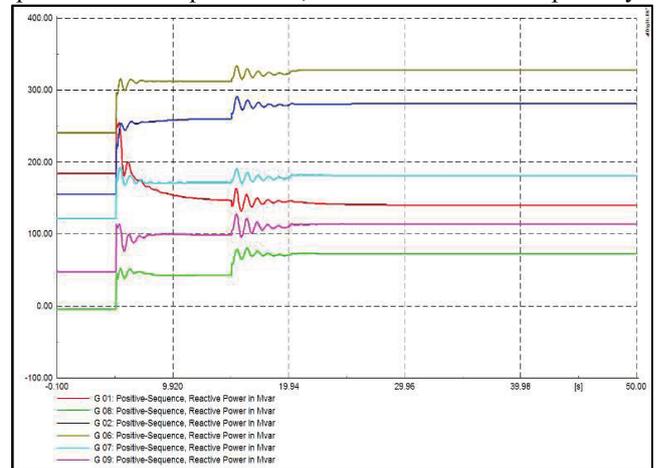

Fig.11. Reactive power responses when SecVC circuits were built and applied in DIgSILENT

3. Integration of MATLAB and DIgSILENT

In this method the same SecVC circuit of the second method was used with same controller parameters but in MATLAB / SIMULINK and then interfaced with DIgSILENT. This method shows typical results of the previous method as shown in Fig. 13.

4. Comparison between schemes

Table VII shows the difference between system with each control scheme and system without SecVC in terms of voltage index (ΔV_{rms}) as illustrated in (19) and power losses. The

results investigated that schemes 2 and 3 have better performance than scheme 1 in terms of voltage deviation index and total power losses.
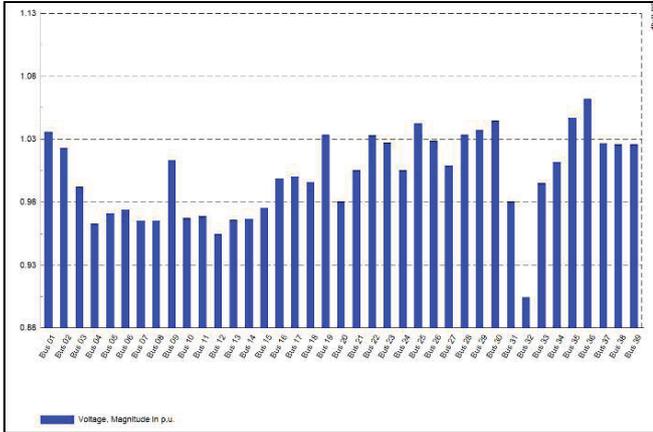

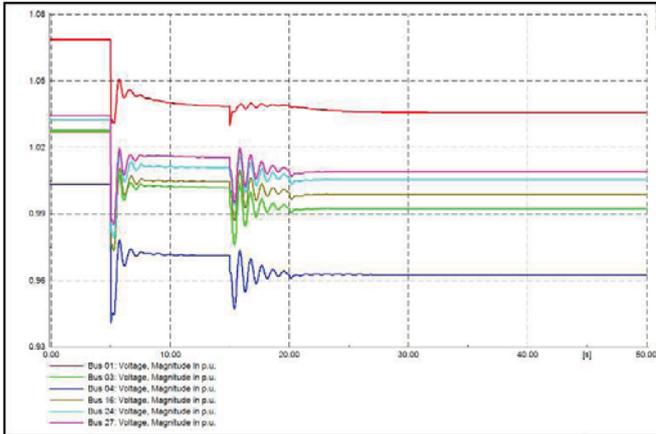Fig. 12. Grid buses Voltage when SecVC circuits were built and applied in DIgSILENT

Fig.13. Pilot buses Voltage responses when DIgSILENT is integrated with MATLAB.

$$\Delta V_{rms} = \sqrt{\frac{1}{n_L}\sum_{i=1}^{n_L}(V_{in} - V_i)^2} \qquad (19)$$

Where n_L is the number of load buses in the power system which is equal to 29 buses in the IEEE 39 bus system. V_{in} is the nominal voltage of the load bus and V_i is the actual load bus voltage. Lower voltage index means better voltage profile.

TABLE VII. COMPARISON BETWEEN THE THREE CONTROL SCHEMES

Point of comparison	Scheme 1	Scheme2	Scheme 3	Without SecVC
Power losses (MW)	52.3	49.1	49.1	58.2
ΔV_{rms}	0.040	0.033	0.033	0.056

VII. CONCLUSIONS

The paper investigates applying Tertiary and secondary voltage control on the New England system.The results show that establishing PI secondary voltage control either in DIgSILENT or MATLAB presented same system performance. Station control results in a small steady state error while the PI secondary voltage control achieved the optimal voltages. The PI secondary voltage control schemes achieved less voltage deviation index and total power losses than station control scheme. The results proved the effectiveness of system partitioning and pilot buses selection methods as all the load busbars in the system achieved the optimal values. The results also proved the ability of DIgSILENT in building new functions or even integrating with other applications to apply various functions in terms of transient analysis.

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