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Hierarchical Control Scheme for two Static Compensators in the Brazilian 45-Bus Power System

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***Abstract*—This paper presents a conventional external scheme for controlling two neighboring Static Compensators (STATCOMs) from a supervisory level. The two STATCOMs are connected to two buses of a load area in a multimachine power system. The power network analyzed in this paper is a 45-bus 10-generator section of the Brazilian power system. Regulating the voltages at the points of connection to the power system is considered to be the primary objective of the local controllers of the two STATCOMs in this study. Based on the deviations of the voltages with respect to their corresponding reference values, the hierarchical control generates the appropriate signals in the form of the auxiliary reference signals for the line voltage control loops in the two devices. Simulation results are provided to show the proposed external controller improves the performance of the power system during small and large scale disturbances.**

***Index Terms*—Static Compensator, FACTS devices, Supervisory level control, Hierarchical control, Multimachine power system, External controller.**

I. INTRODUCTION

STATIC Compensator (STATCOM) is a shunt Flexible AC Transmission System (FACTS) device that is connected to the power system in parallel. By regulating the active and reactive power exchange with the power system, the STATCOM is able to control the voltage at the point of connection to the network [1].

Various techniques have been proposed in the literature, which focus on designing efficient local controllers for a STATCOM. These techniques range from linear techniques in which the power system equations are linearized at a specific operating condition [2]-[5] to nonlinear control designs [6]-[9] and quite recently to intelligent controllers applying fuzzy systems [10]-[12], adaptive neural networks [13] and adaptive critic designs based schemes [14].

While all these control schemes are claimed to have certain advantages over the other similar designs, the performance of the STATCOM can be further improved by employing a hierarchical control scheme, where a higher level external controller observes the performance of the power system and the STATCOM from a supervisory level and based on this it generates appropriate control signals in the form of auxiliary control signals or additional reference set-points applied to the STATCOM.

It has been shown in the literature that external controllers can be designed for the STATCOM in order to control the device from a supervisory level [1]. With the introduction of the appropriate external control scheme, the STATCOM can improve the dynamic stability of the power system, contribute to subsynchronous resonance damping and transient stability [1],[16].

This paper investigates an external control scheme for two STATCOMs connected to a multimachine power system. The system considered in this study is the 45-bus 10-generator section of the Brazilian power network. The two STATCOMs are connected to a load area with low voltages. The proposed external controller provides auxiliary reference signals for the line voltage control loops of the two STATCOMs during the transient and dynamic disturbances in order to minimize the line voltage deviations.

The rest of the paper is organized as follows: Section II of the paper provides a background on the STATCOM structure and the control scheme applied for it. The details of the multimachine power system are presented in Section III. Section IV discusses the structure of the proposed external controller. Simulation results appear in Section V comparing the performance of the system with and without the external controller. Finally, concluding remarks are summarized in Section VI of the paper.

II. STATCOM IN A POWER SYSTEM

Figure 1 shows the schematic diagram of a STATCOM connected to a power system. It consists of a voltage source inverter (VSI), a pulse width modulation (PWM) module and the step-up transformer. The STATCOM is controlled using two decoupled conventional PI controllers. Line voltage deviations and the dc link deviations are passed through two PI controllers which in turn determine the modulation index and inverter output phase shift applied to the PWM module

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respectively. Controlling the voltage *V* at the point of connection to the network is the main objective of the STATCOM considered in this paper.

In a typical STATCOM with a capacitor as the dc link, the values of the active and reactive power are dependent on one another. However, a STATCOM connected to a battery energy storage system (STATCOM-BESS) is capable of controlling the values of the active and reactive power independently [15].

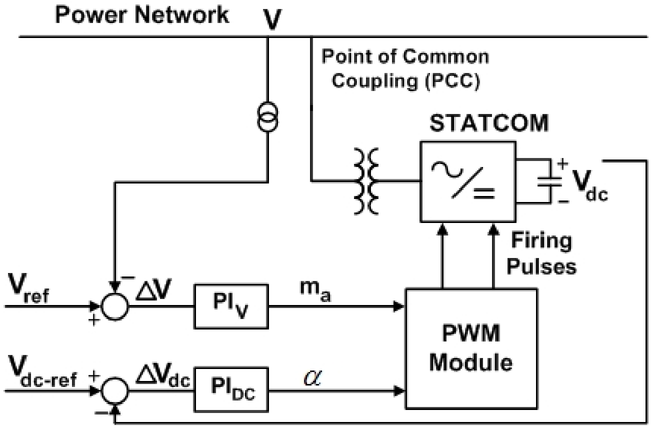

Fig. 1. Schematic diagram of a STATCOM.

Parameters of the STATCOM PI controllers are tuned at one specific operating point, so that the controller provides satisfactory and stable performance when the system is exposed to small changes in reference values as well as large disturbances such as a three phase short circuit on the power network.

III. BRAZILIAN 45-BUS POWER SYSTEM

Figure 2 illustrates the multimachine power system studied in this paper. It is a 45-bus 10-generator power system and represents a section of the Brazilian power grid. The system has two voltage levels of 525 kV and 230 kV respectively, with 14 transmission lines at 525 kV and 41 lines at 230 kV, 24 load buses and 7 buses with shunt compensation. The total installed capacity of the system is 8,940 MVA. All the generators, transformers and transmission lines have been modeled in detail in the PSCAD/EMTDC® environment.

After completing a load flow analysis on the power system in Fig. 2, bus 378 (Joinvile) shows up as having the lowest voltage in the network at 0.92 p.u. It has several transmission lines and shunt loads connected to it. A STATCOM can therefore be connected to this bus in order to improve the voltage stability and to control the voltage during dynamic disturbances. For a detailed explanation of the system, the optimal allocation of the STATCOM and its impact on the steady state and dynamic performance of the system the reader is referred to the authors' previous work in [17].

Table I presents the load flow results on the powe system in Fig. 2 before and after installing the STATCOM of the size 90 MVar at bus 378.

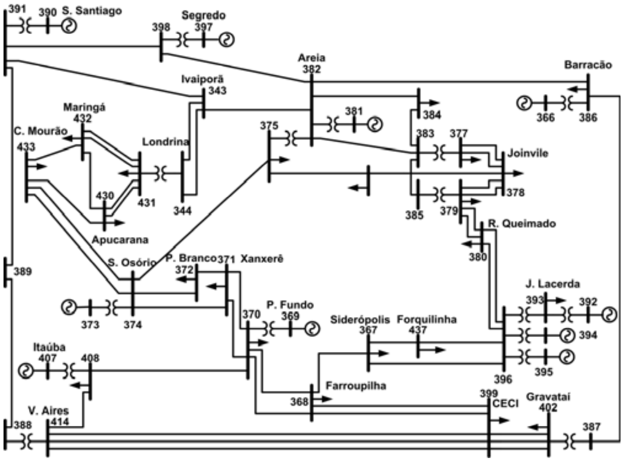

Fig. 2. Brazilian 45-bus power network.

TABLE I

LOAD FLOW RESULTS

BUS #	NO STATCOM	SINGLE STATCOM 90 MVAR	TWO STATCOM'S 45 MVAR EACH
343	1.039	1.043	1.042
344	1.029	1.033	1.033
366	1.02	1.02	1.02
367	0.967	0.973	0.973
368	1.018	1.021	1.021
369	1.04	1.04	1.04
370	1.017	1.018	1.018
371	0.987	0.988	0.988
372	0.979	0.98	0.98
373	1.02	1.02	1.02
374	0.994	0.995	0.995
375	1.001	1.009	1.008
376	0.977	0.998	0.997
377	0.983	1.007	1.006
378	0.927	0.977	0.968
379	0.961	0.991	0.994
380	0.969	0.987	0.988
381	1.022	1.022	1.022
382	1.029	1.033	1.033
383	0.986	1.007	1.007
384	0.987	1.006	1.006
385	0.968	0.997	0.998
386	1.028	1.031	1.031
387	1.034	1.037	1.037
388	1.048	1.051	1.051
389	1.051	1.053	1.053
390	1.018	1.018	1.018
391	1.039	1.041	1.041
392	1.03	1.03	1.03
393	0.995	0.999	0.999
394	1.03	1.03	1.03
395	1.03	1.03	1.03
396	0.998	1.004	1.004
397	1.02	1.02	1.02
398	1.031	1.034	1.033
399	1.04	1.043	1.043
402	1.049	1.052	1.052
407	1	1	1
408	0.989	0.99	0.99
414	1.053	1.056	1.056
430	0.994	0.997	0.997
431	1.013	1.017	1.017
432	0.981	0.985	0.985
433	0.97	0.972	0.972
437	0.965	0.971	0.972

It can be seen in Table I that installing a STATCOM at the bus with the lowest voltage can improve the voltage magnitudes of the other neighboring buses, namely buses 377, 379, 380, 383 and 385.

Another alternative is to install two different STATCOMs with half the rating, i.e., 45 MVar each, to buses 378 and 379. This way, the two STATCOMs can interact during the transient faults and disturbances applied to the power system in order to help damp out the voltage deviations faster and more effectively. Table I summarizes the load flow results for this case. The two schemes can also be compared during the steady state conditions. A cost function *J*(*t*) is defined to penalize the voltage deviations of the buses in Fig. 2 from the desired value of 1.0 p.u.

$$J = \sum_{i=1}^{45} w_i \times |1 - V_i| \tag{1}$$

The nonlinear coefficients w_i in (1) depend on the magnitude of the voltage deviation for each bus:

$$w_i = \begin{cases} 1.0 & if\ \ |1 - V_i| \le 0.02 \\ 1.25 & if\ 0.02 < |1 - V_i| \le 0.04 \\ 1.5 & if\ \ |1 - V_i| > 0.04 \end{cases} \tag{2}$$

The values of the cost functions for the three cases in Table I are summarized in Table II. It can be seen that the case with two STATCOM's connected to buses 378 and 379 is as effective in reducing the cost function as the case with a single STATCOM being connected to bus 378.

TABLE II

COST FUNCTIONS CORRESPONDING TO CASES IN TABLE I.

CASE	NO STATCOM	SINGLE STATCOM 90 MVAR	TWO STATCOM'S 45 MVAR EACH
COST FUNCTION *J*	1.172	1.0258	1.026

IV. SUPERVISORY LEVEL CONTROL OF THE TWO STATIC COMPENSATORS

Figure 3 illustrates the schematic diagram of the external controller proposed in this study. The controller receives the line voltage deviations at the buses where the two STATCOMs are connected to, i.e., buses 378 and 379. In turn, it generates two auxiliary reference signals which will be then applied to the reference signals of the line voltage control loops of the two STATCOMs.

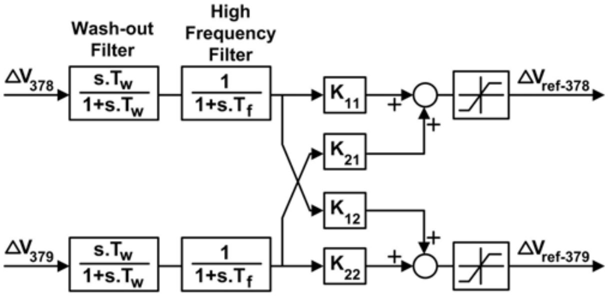

Fig. 3. Schematic diagram of the STATCOM external controller.

Each path of the external controller has two filters. The wash-out filter has a large time constant which is selected as 10.0 sec in this study. This component prevents the external controller from responding to line voltage deviations with very slow dynamics, which will be dealt with by the local controllers of the two STATCOMs.

A second filter is employed which filters out the high frequency content of the line voltage deviations, which is mostly related to the measurement noise. Preventing the external controller from reacting to the high frequency oscillations provide a smoother control signal generated.

The signals provided by the external controller are bound in a way that at no point in time the line voltage at buses 378 and 379 go beyond the range of [0.95,1.05] p.u.

Clearly, the control commands generated by the external controller are temporary signals responses to the line voltage deviations during transient conditions. Therefore, the external controller does not change the voltage set-points of the two STATCOMs permanently.

It should also be noted that with the external controller shown in Fig. 3, the STATCOM line voltage PI controller in Fig. 1 has a new voltage reference. For instance, for the case of the STATCOM connected to bus 378:

$$V_{ref-378}^{new}(t) = V_{ref-378} + \Delta V_{ref-378}(t) \tag{3}$$

where $\Delta V_{ref\text{-}378}$ is the corresponding output of the external controller. However, the line voltage deviation shown in Fig 3, i.e., the input to the external controller, is defined as the difference between the actual value of the line voltage at bus 378 and the original reference signal:

$$\Delta V_{378}(t) = V_{ref-378} - V_{378}(t) \tag{4}$$

Figure 4 illustrates the schematic diagram of the local and external controllers for the STATCOM connected to bus 378.

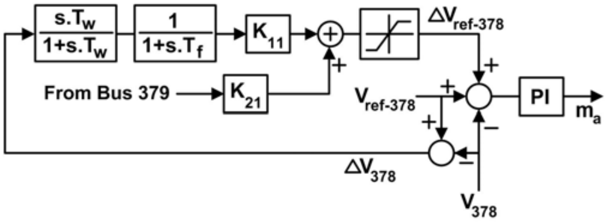

Fig. 4. Schematic diagram of the local and the external controllers for the STATCOM connected to bus 378.

V. SIMULATION RESULTS

Several tests have been applied to the power system and the performances of the two STATCOMs with and without the external controller have been compared. In addition, a new cost-function is defined that takes the voltage deviations during the transient performance of the power system into account:

$$J(N) = \frac{1}{N}\sum_{k=1}^{N}\left[\sum_{i} w_i \times |V_{i,ref} - V_i(k)|\right] \tag{5}$$

where *N* is the length of the vector of the line voltages and i denotes the two buses 378 and 379.

In the first test, a three phase short circuit is applied to one of the transmission lines connecting buses 377 and 378. The fault is cleared after 75 ms and the transmission line is switched back onto the system. Figures 5 and 6 show the voltage at the two buses 378 and 379.

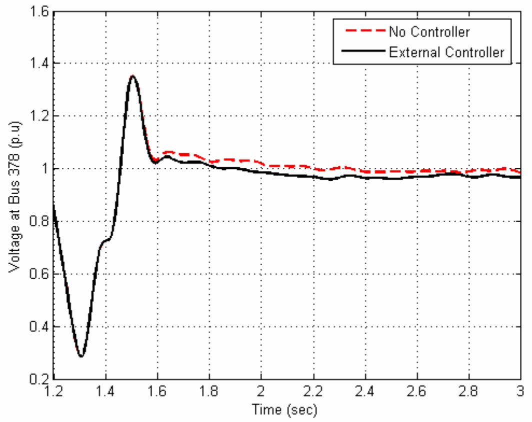

Fig. 5. Voltage at bus 378 during a 75 ms three phase short circuit at the transmission line connecting buses 377 and 378.

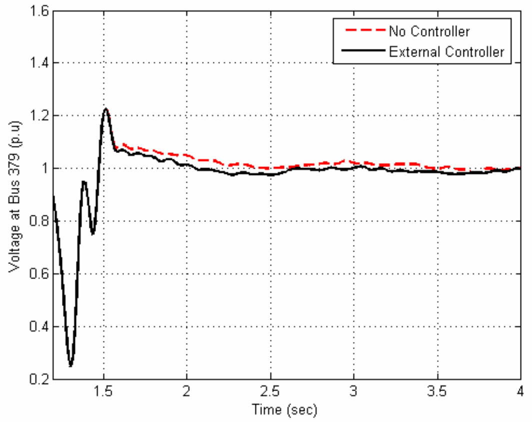

Fig. 6. Voltage at bus 379 during a 75 ms three phase short circuit at the transmission line connecting buses 377 and 378.

In another test, a shunt load is connected to the bus 378 and disconnected after 4 seconds. Figures 7 and 8 summarize the simulation results.

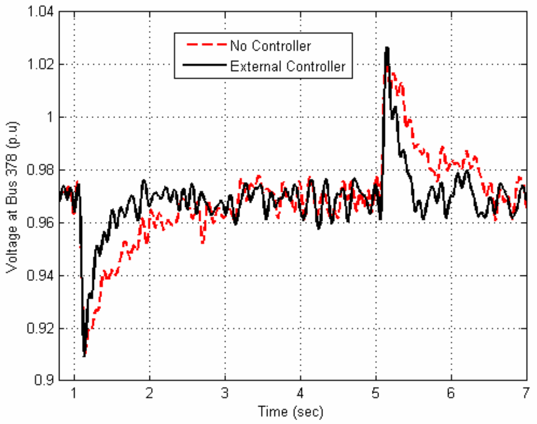

Fig. 7. Voltage at bus 378 when a shunt load is switched on at 1 sec and after 4 seconds is switched off.

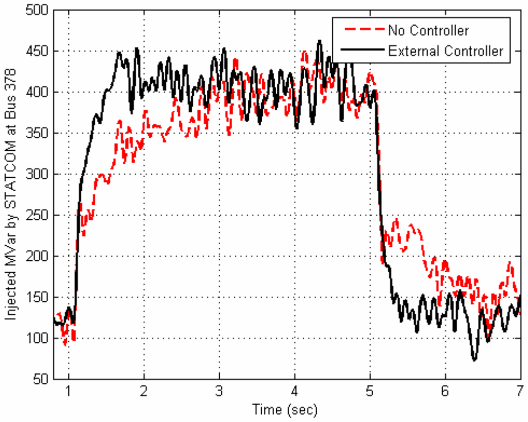

Fig. 8. Reactive power injected by the STATCOM connected to bus 378 when a shunt load is switched on at 1 sec and after 4 seconds is switched off.

Table III summarizes the cost function J defined in (5) for the two cases above. It can be seen that the external controller reduces the bus voltage deviations with respect to their corresponding reference values.

TABLE III
COST FUNCTIONS CORRESPONDING TO THE SIMULATION RESULTS.

CASE	NO EXTERNAL CONTROLLER	EXTERNAL CONTROLLER
THREE-PHASE SHORT CIRCUIT AT LINE 377-378	0.471	0.4373
SHUNT LOAD SWITCH ON/OFF	0.2748	0.2457

VI. CONCLUSIONS

A conventional hierarchical controller was proposed in this paper that controls two Static Compensators (STATCOMs) from a supervisory level. The two STATCOMs are connected to two buses in a single load area in a multimachine power system. The power network studied in this paper is the 45-bus 10-generator section of the Brazilian power system. The proposed hierarchical control scheme, also referred to as the external controller in this study, receives the voltage deviations of the two buses and based on this information generates two control signals in the form of auxiliary commands. These commands are then added to the line voltage reference signals of the two STATCOMs.

Simulation results were provided that indicate the proposed external controller manages to reduce the voltage deviations at the buses where the STATCOMs are connected to, during the small and large scale disturbances.

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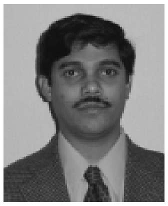
VIII. BIOGRAPHIES

Salman Mohagheghi (M’99) was born in Manchester, UK in 1976. He completed his B.Sc. and M.S degrees in Electrical Power Engineering from University of Tehran and Sharif University of Technology, Tehran, Iran in 1998 and 2001 respectively. He started his graduate studies at Georgia Institute of Technology, Atlanta GA in 2001, where he is currently a research assistant working towards his PhD degree. His research focuses on the applications of computational intelligence techniques on wide area (supervisory level) monitoring and control of interconnected power systems. His areas of interest include power system stability and dynamics, systems and control, fuzzy and neural systems. He was the President of the Iranian Student Association at Georgia Tech in 2003-05 and the Vice-President of the IEEE Power Engineering Society Student Chapter at Georgia Tech in 2003-06.

Yamille del Valle was born in Antofagasta, Chile. She received the Civil Industrial Engineering degree, Electrical Engineering major, from Catholic University of Chile in 2001 and the MS degree from Georgia Institute of Technology in 2005. She was lecturer and researcher in the Department of Electrical Engineering, University of Chile during 2002 and 2003. Currently, she is pursuing a Ph. D. degree in Electrical Engineering at Georgia Institute of Technology. Ms. del Valle is part of the Power System and Power Electronics research group. Her main interests include Evolutionary Computation Techniques applied to Power System problems and Optimal Allocation of FACTS devices.



Ganesh Kumar Venayagamoorthy received his PhD degree in Electrical Engineering from the University of Natal, Durban, South Africa, in February 2002. He is currently an Assistant Professor of Electrical and Computer and the Director of the Real-Time Power and Intelligent Systems Laboratory at University of Missouri, Rolla. His research interests are in computational intelligence, power systems control and stability, evolvable hardware and signal processing. He has published over 140 papers in refereed journals and international conferences.

Dr. Venayagamoorthy is the recipient of the following awards - 2005 IEEE Industry Application Society (IAS) Outstanding Young Member award, the South African Institute of Electrical Engineers Young Achiever’s award, 2004 NSF CAREER award, the 2004 IEEE St. Louis Section Outstanding Young Engineer award, the 2003 International Neural Network Society (INNS) Young Investigator award, 2001 IEEE Computational Intelligence Society (CIS) W. J. Karplus summer research grant and five prize papers with the IEEE IAS and IEEE CIS. He is a Senior Member of the IEEE and the South African Institute of Electrical Engineers, a Member of INNS and the American Society for Engineering Education. He is an Associate Editor of the IEEE Transactions on Neural Networks. He is currently the IEEE St. Louis IAS Chapter Chair, the Chair and the founder of IEEE St. Louis CIS Chapter, the Chair of the Task Force on Intelligent Control Systems and the Secretary of the Intelligent Systems subcommittee of IEEE Power Engineering Society. Dr. Venayagamoorthy was the Technical Program Co-Chairs of the 2003 International Joint Conference on Neural Networks, Portland, OR, USA and the 2004 International Conference on Intelligent Sensing and Information Processing, Chennai, India. He has served as member of the program committee, organized and chaired sessions, and presented tutorials at several international conferences and workshops.

Ronald G Harley (M’77-SM’86-F’92) received the MScEng degree (cum laude) in electrical engineering from the University of Pretoria, South Africa in 1965, and the Ph.D. degree from London University in 1969.

In 1971 he was appointed to the Chair of Electrical Machines and Power Systems at the University of Natal in Durban, South Africa. At the University of Natal in South Africa he was a professor of Electrical Engineering for many years, including the Department Head and Deputy Dean of Engineering. He is currently the Duke Power Company Distinguished Professor at the Georgia Institute of Technology, Atlanta, USA. His research interests include the dynamic behavior and condition monitoring of electric machines, motor drives, power systems and their components, and controlling them by the use of power electronics and intelligent control algorithms.

Dr. Harley has co-authored some 380 papers in refereed journals and international conferences and three patents. Altogether 10 of the papers attracted prizes from journals and conferences. He is a Fellow of the British IEE, and a Fellow of the IEEE. He is also a Fellow of the Royal Society in South Africa, and a Founder Member of the Academy of Science in South Africa formed in 1994. During 2000 and 2001 he was one of the IEEE Industry Applications Society's six Distinguished Lecturers. He was the Vice-President of Operations of the IEEE Power Electronics Society (2003-2004) and Chair of the Atlanta Chapter of the IEEE Power Engineering Society. He is currently Chair of the Distinguished Lecturers and Regional Speakers program of the IEEE Industry Applications Society. He received the Cyrill Veinott Award in 2005 from the Power Engineering Society for “O*utstanding contributions to the field of electromechanical energy conversion”.*