

X SEPOPE

21 a 25 de maio de 2006
May – 21st to 25th – 2006

FLORIANÓPOLIS (SC) – BRASIL

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**X SYMPOSIUM OF SPECIALISTS IN ELECTRIC OPERATIONAL
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**MODIFIED PI CONTROL OF A GATE-CONTROLLED SERIES CAPACITOR FOR
A 45-BUS SECTION OF THE BRAZILIAN POWER SYSTEM**

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SUMMARY

This paper presents the use of a nonlinear approximator to provide better controllability to the proportional-integral (PI) control method applied to a Gate-Controlled Series Capacitor (GCSC). The GCSC has been installed in a 45-bus section of the Brazilian power system, in one of the two parallel lines between buses 430 and 431. The GCSC is used to provide power flow control in the transmission line and to damp transient power oscillations for changes in the system conditions. In the proposed control method, the PI controller provides the compensating reactance while the neural network approximator estimates the corresponding blocking angle for firing the gate-turn off devices in the GCSC. Due to the existence of simple relationship between the power flow in the transmission line and the compensating capacitive reactance, the PI controller performs better with compensating reactance as its output instead of blocking angle. For power flow changes and disturbances in the system, the modified PI controller provides better damping compared to the conventional PI.

KEYWORDS

GCSC, Modified PI control, 45-bus Brazilian System, Neural Networks.

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1. Introduction

Nowadays deregulated market demands more generation units and more power transmission and less transmission and distribution losses. It also needs to utilize every existing system in an optimized manner as it is becoming increasingly difficult to build new electric power transmission lines due to restrictions imposed by financial and environmental issues. As the power consumption is increasing, the existing transmission lines have to be operated more efficiently and close to their stability and/or thermal limits in the future. The Flexible AC Transmission Systems (FACTS) devices have made it possible to control the real and/or the reactive power flow in a transmission line dynamically which not only satisfy the market requirements but also improve the transient performance of the power system. Most commonly used FACTS devices are the series transmission devices which includes the Thyristor Controlled Series Capacitor (TCSC) and the Static Synchronous Series Compensator (SSSC). There are several installations of TCSC in the world [1-2]. The Brazilian North South Interconnection with a TCSC to damp out low frequency inter-area oscillation is one of the good examples of TCSC installation in the world because it leads to a very important expansion in Brazilian power systems. Recently, a new series FACTS device, the Gate-Controlled Series Capacitor (GCSC) has been proposed [3-5] which has advantages over TCSC with regard to the size of the capacitor being smaller and that no reactor is required. The SSSC [6-7] is a more complete device in terms of flexibility than the GCSC, however, its cost and complexity is much higher than GCSC.

The series line reactance is one of the main factors which govern the maximum power flow through a transmission line. The conventional technique for real power control is to use fixed capacitors in series with the transmission line [8], thus reducing effective inductive reactance of the line. As a good example of series capacitor installation in the world, the Sao Joao do Piaui series compensation system using fixed capacitor banks has been found as a economic solution to the growing power demand in Brazilian industries and was commissioned in 2003. This method can increase the real power flow in the line and can achieve stability limit close to its thermal limits. But fixed capacitors do not provide options for dynamically controlling the power flow according to the requirements which may vary over time. Thus, the advantage of deploying series FACTS devices (TCSC and GCSC) for such conditions because with thyristor or gate-controlled switch (like GTO or IGCT), the effective capacitive reactance of the compensator can be quickly varied providing dynamic control of real power flow in a line over certain range of operation. In addition, it can provide damping to the system during transients if the capacitor is sized properly. Though, the GCSC sizing may be different for optimal power flow control and for optimal damping control.

The GCSC is a nonlinear power electronic device. The relation between the blocking angle of the GCSC and the effective capacitive reactance provided by the GCSC is nonlinear. Thus, a nonlinear solution is needed to find blocking angle for each operating point. The neural network has been proven effective for approximating any nonlinear function with sufficient accuracy [9]. In this paper, it has been shown that the use of a neural network for approximation of the nonlinear function of blocking angle in terms of the effective capacitive reactance, provides good performance in adjunct with a proportional-integral control. The proposed GCSC control method has been simulated on the 45-bus section of the Brazilian power system.

2. Gate-Controlled Series Capacitor

The Gate-Controlled Series Capacitor is composed of two anti-parallel gate-controlled switches and a capacitor bank in series with the transmission line as shown by the single line diagram in Fig. 1. If the switches are turned on all the time then the capacitor is by-passed and it does not provide any compensation. However, if the switches are turned off once per cycle at a determined blocking angle of α , the capacitor in series with the transmission line turns on and off alternately and a voltage V_c appears across the capacitor. The GCSC has a great advantage over TCSC as the blocking angle α can be varied continuously thus varying the fundamental components of V_c , in contrast to the TCSC firing angle which is discontinuous due to the zone in which a parallel resonance occurs between the Thyristor Controlled Reactor (TCR) and the capacitor [4].

In the GCSC, a blocking angle of 90 degrees means that the capacitor is fully inserted and a blocking angle of 180 degrees means that the capacitor is fully by-passed making effective capacitive reactance zero. The reactance dynamic control range for GCSC can be varied from 0 to X_{max} unlike TCSC where it can only vary between X_{min} to X_{max} , where $X_{min} > 0$. Also, GCSC does not need an extra reactor unlike the TCSC; this reduces the cost of the device. For these reasons, the GCSC might be a better solution in most situations than other controlled series compensators for future deployments. Different multi-modular structure of the GCSC has been discussed in [5]. For simplicity, only the single module structure of GCSC is considered in this paper.

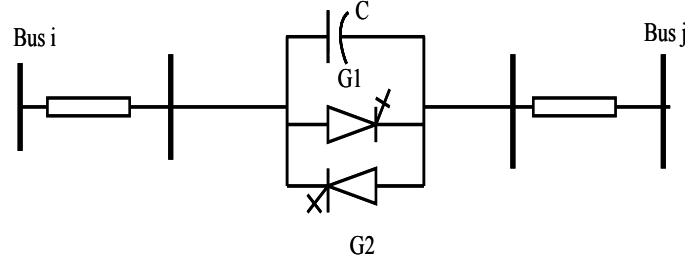


Fig. 1 Schematic diagram of a GCSC inserted between buses i and j in a transmission line.

The GCSC could be used in applications where fixed capacitive compensation, TCSC or SSSC is used today, mainly to control power flow and provide damping of power and generator speed oscillations. The GCSC can operate in an open loop mode controlling the capacitive reactance added in series with the transmission line. It can also operate in a closed loop mode where it controls the real power flow in the transmission line or maintain a constant compensation voltage. One interesting point is that GCSC can be used to retrofit existing fixed series compensation just by adding controlled switches and its controller to the fixed capacitor bank.

3. Modified PI Control

Due to the wide saturation region and highly nonlinear relationship of the capacitive compensation reactance and the blocking angle (Fig. 2), the PI controller has difficulties to provide blocking angle directly. But, the relationship between the compensating reactance and the power flow in the transmission line is relatively simple. Hence, a PI controller outputting the compensating reactance performs better. Thus, in the proposed control method, a neural network function approximator is trained offline using the relationship between X_{ceff} and blocking angle α given by (1).

$$X_{ceff} = \frac{X_c}{\pi} [2\alpha - 2\pi - \sin 2\alpha] \quad (1)$$

Here, X_c is the total installed reactance of the capacitor bank. The neural network with 1 input linear neuron, 3 sigmoidal neurons in the hidden layer and one output linear neuron (Fig. 3) is batch trained for the complete range of blocking angle - 90° to 180° . After the MLP approximator is trained to estimate the blocking angle from the effective capacitive reactance value, the approximator is connected after a PI controller which provides the effective capacitive reactance required at each instance. In the controller block diagram (Fig. 4), when switch S is in position 1, the output of the PI controller subtracted from 180° (α) is fed to the firing circuit according to the typical GCSC control method and when S is in position 2, the output of the approximator (α) is fed to the GCSC firing circuit directly (the proposed modified PI control scheme). This proposed design incorporates nonlinearity in the traditional linear controller. The modified PI control uses the neural network to eliminate the need of a table and exhaustive search while providing the nonlinear characteristics in the linear PI control method.

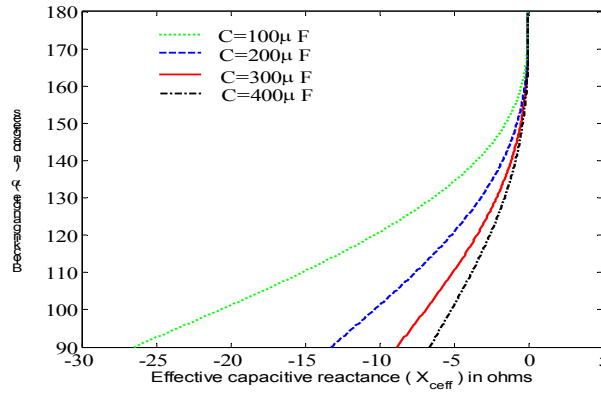


Fig. 2 The plot for effective capacitive compensation vs. blocking angle.

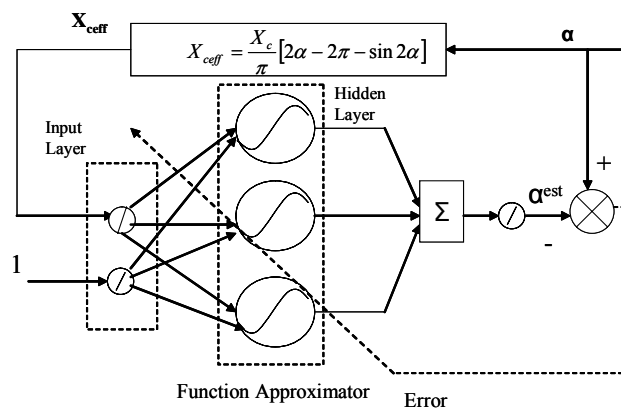


Fig. 3 Training of the function approximator (neural network) to estimate the blocking angle.

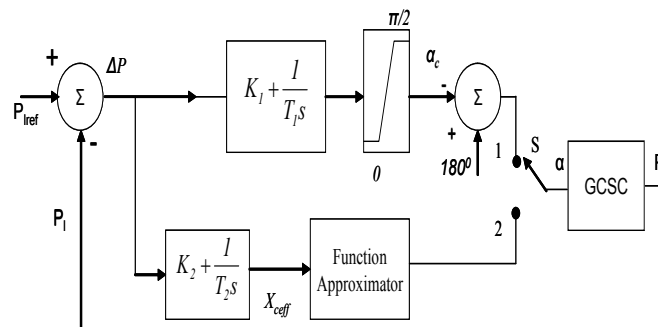


Fig. 4 The control block diagram of the GCSC with PI (switch S at position 1) and PI-MLP controller.

4. 45-Bus Brazilian Power System

All the generators in Fig. 5 are modeled in detail, with the AVR, exciter, turbine and governor dynamics taken into account. The system is simulated in the PSCAD/EMTDC environment.

The main characteristics of the power system are as follows:

- 10 generators

- Two voltage levels of 525 kV and 230 kV,
- 14 transmission lines at 525 kV,
- 41 transmission lines at 230 kV,
- 24 load buses,
- 7 buses with shunt compensation,
- Total installed capacity of 8,940 MVA.
- The GCSC has been installed in one of the lines between buses 430 and 431.

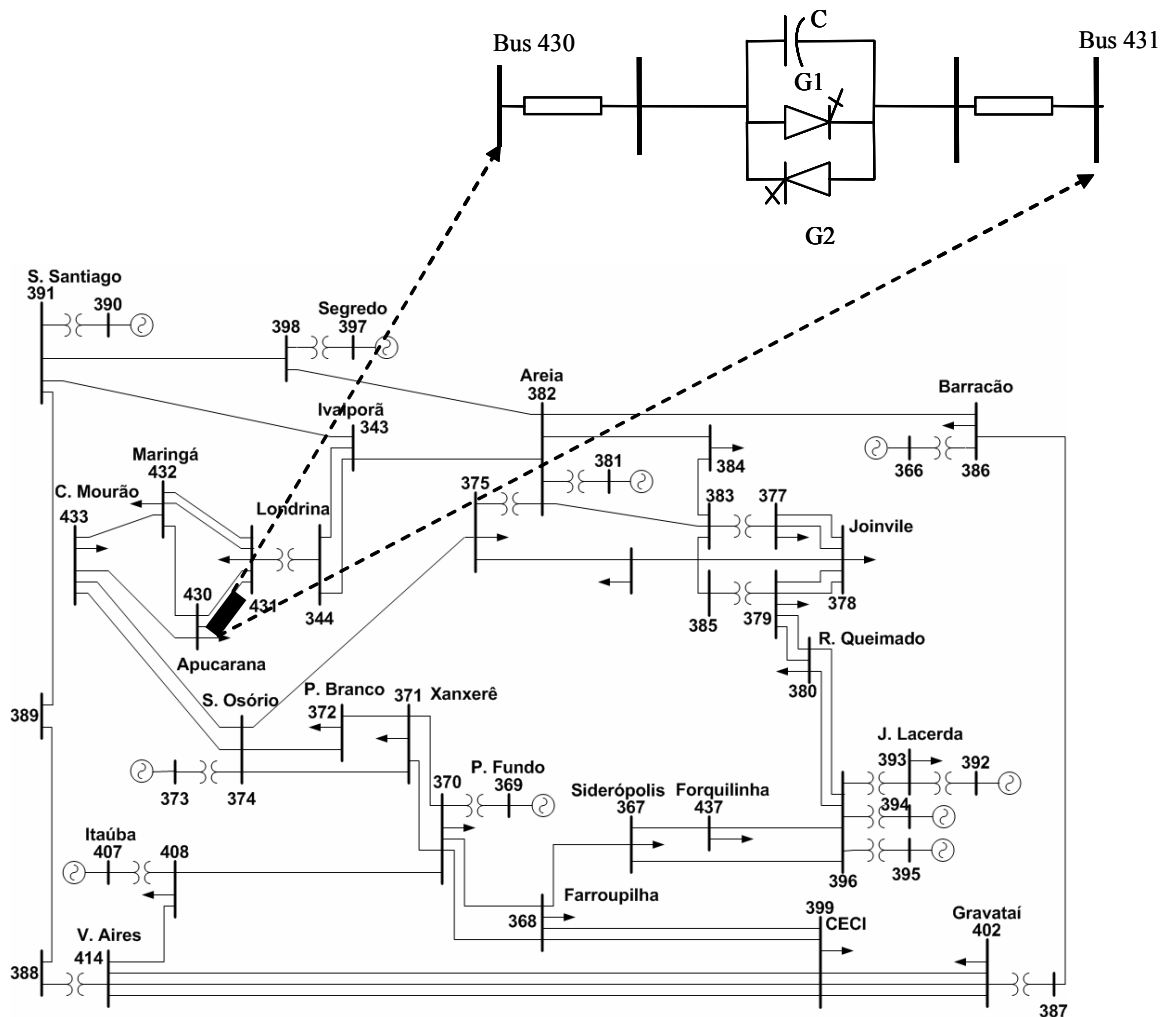


Fig. 5 One line diagram of a 45 bus section of Brazilian Power System with one GCSC.

5. Results

The GCSC is installed near the low voltage bus to alleviate the active power flow to the section of the system. Fig. 6 show a step change in the reference of line power and the corresponding response of blocking angle (α) with the proposed modified PI control method (PI-MLP method). Fig. 7 shows the response in the power flow through the GCSC connected line under a 3- Φ short circuit fault of 100 ms duration. Before the disturbance the blocking angle of the GCSC is 120 degrees and power flow through the line with the GCSC is 140 MW. The PI-MLP shows improvement in the initial overshoot although a small amplitude persistent inter-area oscillation in the power is visible. Fig. 8 shows the response of the line power due to a temporary outage (200 ms.) of the parallel line between buses 430 and 431. The PI-MLP control provides better damping than the PI controller. Similar conclusion can be drawn from a temporary load change test (Fig. 9) where a 100 % load change is simulated for 200

ms at bus 430. The original load at that bus is 132 MW and 6.6 Mvar. The PI-MLP control method shows better damping.

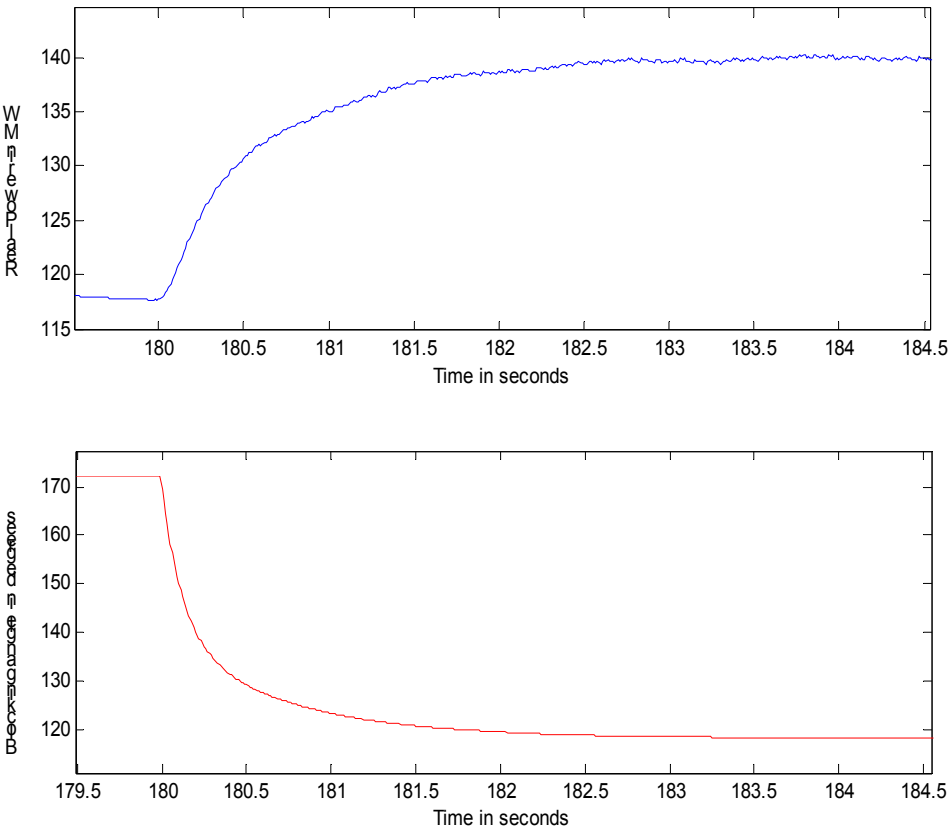


Fig. 6 Step change in real power flow through the line 430-431 and corresponding blocking angle.

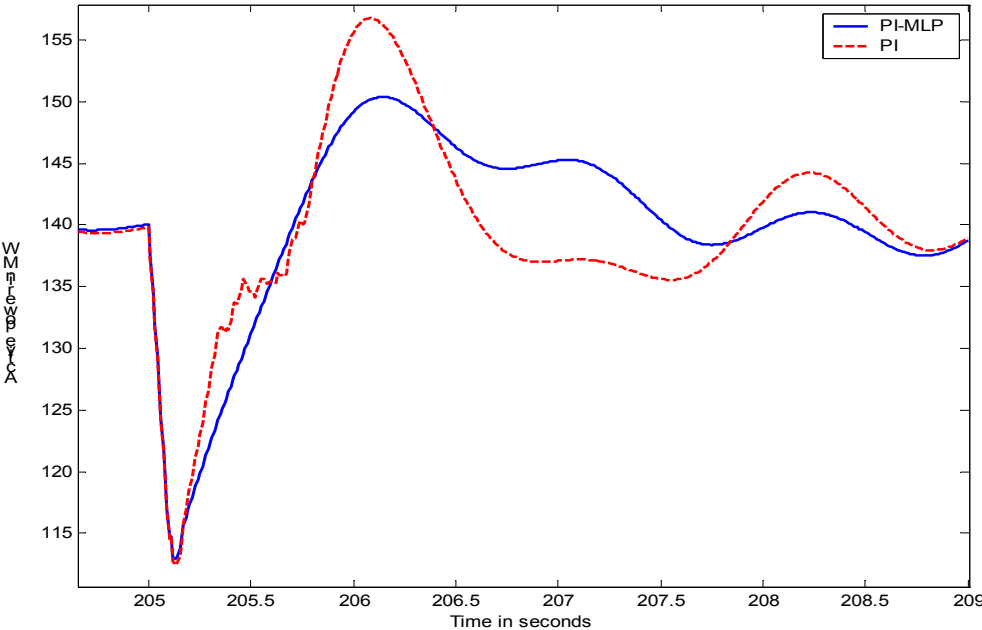


Fig. 7 Active power flow response under 3-phase short circuit fault at bus 430 for 100 ms duration.

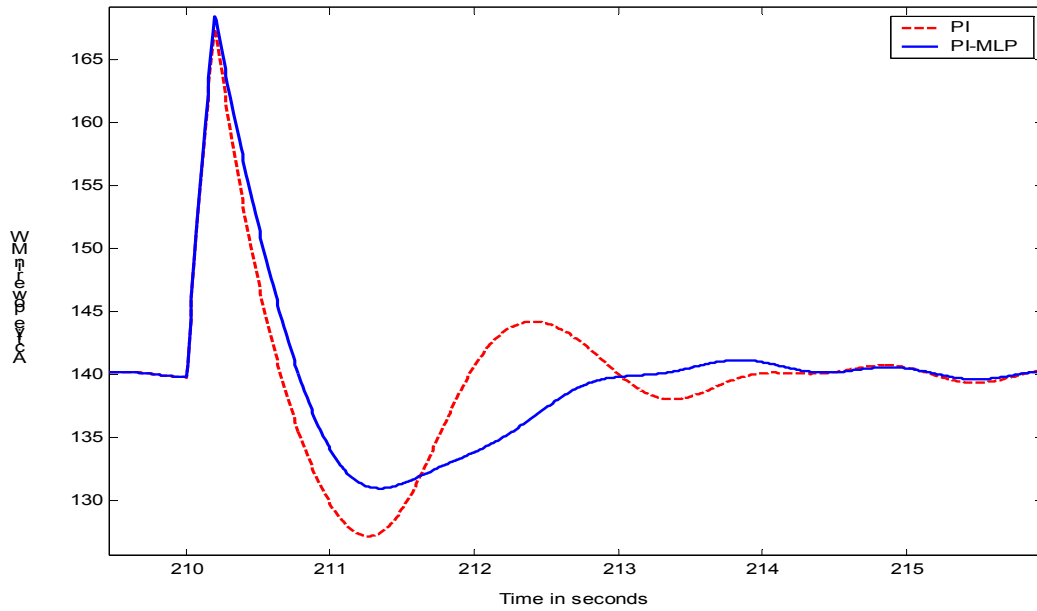


Fig. 8 Active line flow response for 200 ms duration temporary outage of the second line between buses 430 and 431.

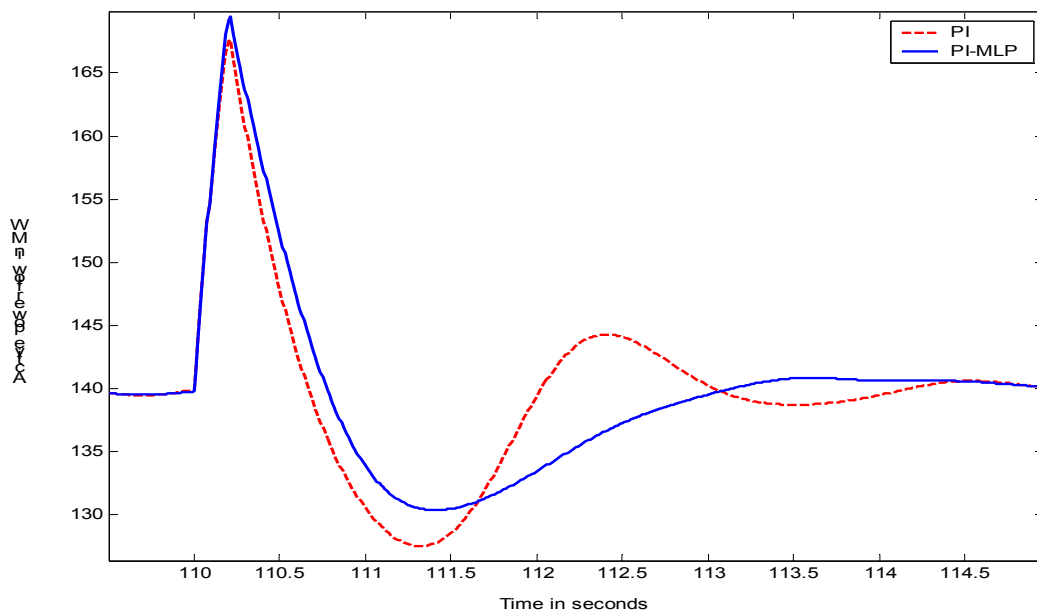


Fig. 9 Active power flow through the GCSC for a temporary load change at bus 430.

6. Conclusions

In this paper, a single GCSC device has been placed in the 45-bus section of the Brazilian power system. This enables the active power flow through the transmission line to be controlled. The GCSC is a controlled variable capacitor device which can provide reactive compensation in series with a transmission line. Thereby it changes the inductive reactance of the transmission line. The compensation helps to regulate power flow as well as provide damping to the power flow oscillations. As the GCSC is a nonlinear device with nonlinear relationship between the blocking angle and the reactive compensation, a linear PI control method is improved by cascading a neural network approximator to the PI control. The linear PI control provides the compensating reactance which is then translated to the blocking angle through the neural network approximator.

The proposed controller provides better performance during power flow changes and under disturbances like short circuit faults, line outages and load changes. A small neural network of this kind with fixed weights can easily be implemented on a cheap microprocessor and can be cascaded with an existing PI controller. Hence, the proposed method is cost effective and a viable neural network based control method for real world power system application.

BIBLIOGRAPHY

- [1] C. Gama, "Brazilian North-South Interconnection control-application and operating experience with a TCSC", IEEE Power Engineering Society Summer Meeting, vol. 2, July 1999, pp. 1103 – 1108.
- [2] J. F. Hauer, W. A. Mittelstadt, R. J. Piwko, B. L. Damsky and J. D. Eden, "Modulation and SSR tests performed on the BPA 500 kV thyristor controlled series capacitor unit at Slatt substation", IEEE Transactions on Power Systems, vol. 11, issue 2, May 1996, pp. 801-806.
- [3] L. F. W. de Souza, E. H. Watanabe and M. Aredes, "GTO controlled series capacitor", Proc. IEEE Power Engineering Society Winter Meeting, vol. 4, Jan. 2000, pp. 2520-2525.
- [4] L. F. W. de Souza, E. H. Watanabe, J. E. R. Alves and L. A. S. Pilotto, "Thyristor and gate controlled series capacitors: comparison of components rating", Proc of IEEE Power Engineering Society General Meeting, vol. 4, July 2003, pp. 2542-2547.
- [5] L. F. W. de Souza, E. H. Watanabe and M. Aredes, "GTO controlled series capacitors: multi-module and multi-pulse arrangements", IEEE Transactions on Power Delivery, vol. 15, no. 2, Apr. 2000, pp. 725 – 731.
- [6] F. A. L. Jowder, "Influence of mode of operation of the SSSC on the small disturbance and transient stability of a radial power system", IEEE Transactions on Power System, vol. 20, Issue 2, May 2005, pp. 935 – 942.
- [7] Xiao-Ping Zhang, "Advanced modeling of the multicontrol functional static synchronous series compensator (SSSC) in Newton power flow", IEEE Transactions on Power Systems, vol. 18, Issue 4, Nov. 2003, pp. 1410 – 1416.
- [8] L. Kirschner, M. C. Lima, J. E. C. Fernandes and R. Munchmeier, "Benefits and design aspects of Sao Joao do Piaui 500 kV series capacitor", Transmission and Distribution Conference and Exposition: Latin America, Nov. 2004, pp. 17 – 21.
- [9] F. Girosi; T. Poggio, "Neural Networks and best approximation property," *Biolog Cybernetics*, vol. 63, 1990, pp. 169-176.
- [10] P. M. Anderson, A. A. Fouad, *Power system control and stability*, New York, IEEE Press, 1994, ISBN 0-7803-1029.