2006 International Joint Conference on Neural Networks
Sheraton Vancouver Wall Centre Hotel, Vancouver, BC, Canada
July 16-21, 2006

Real-Time Implementation of an Optimal Transient Neurocontroller for a GCSC

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Abstract—**This paper presents the design of an optimal Auxiliary Transient Neurocontroller (ATNC) for the Gate Controlled Series Capacitor (GCSC) in a multi-machine power system. GCSC is a recent advancement in the family of series FACTS devices. While GCSC regulates power flow through a transmission line, an auxiliary control signal can provide damping to the power oscillations during disturbances. The ATNC has been designed using heuristic dynamic programming to develop an optimal neurocontroller with fixed weights. The ATNC is implemented in real-time using the TMS3206701 DSP and the Real-Time Digital Simulator (RTDS). Results are presented to show the effectiveness of the ATNC in damping transient oscillations during disturbances.**

I. INTRODUCTION

IN the recent years, it is becoming increasingly difficult to build new transmission lines due to restrictions imposed by financial and environmental issues. As the electric power consumption is increasing, the existing transmission lines have to be operated more efficiently and close to their stability limits in the future. The Flexible AC Transmission System devices (FACTS) have made it possible to control the real and/or reactive power flow in a transmission line dynamically which not only helps to satisfy the market strategies but also improves the transient performance of the system. Most commonly used FACTS devices are series transmission devices which includes Thyristor Controlled Series Compensator (TCSC), Static Switched Series Compensator (SSSC). Recently another FACTS device, Gate Controlled Series Capacitor (GCSC) has been proposed by Watanabe [1-3] which show improved performance over TCSC with smaller size capacitor and absence of line reactor.

The series line reactance is one of the main factors which govern the maximum power flow through a transmission line stably. The usual technique for real power control is to use fixed capacitors in series with the transmission line to reduce the effective inductive reactance of the line. 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 controlling the power flow according requirements which might be different at different times. Here comes the advantage of series FACTS devices like TCSC and GCSC. With thyristor or GTO controlled series capacitors, the effective capacitive reactance of the compensator can be varied providing control of real power flow in a line over certain range of operation dynamically and thus it not only provides control over different steady-state operating zones but also provides transient stability to the system during sudden disturbances.

A simple GCSC device is composed of a capacitor bank and anti-parallel GTOs in parallel with the capacitor bank in each phase. Because of simple architecture and no need of an extra reactor unlike TCSC, this device is likely to replace the existing fixed capacitors and TCSCs in future. The fixed capacitor banks can be converted to FACTS devices by placing the anti-parallel GTOs.

The GCSC is a relatively inexpensive new series FACTS device which has the potential to be widely applied to the power system in the near future. Thus, the nonlinear optimal control will eventually become necessary to maximize the benefits of a GCSC when integrated into electric power grid. While model based indirect adaptive neurocontrol schemes have been shown effective for controlling nonlinear systems [4-6], it is computationally intensive for practical purposes due to continually online training and it is difficult to guarantee stability of such controllers unconditionally. Alternative approaches for neurocontroller designs based on Heuristic Dynamic Programming (HDP), a member of the Adaptive Critic Design (ACD) family have been proven effective in providing stable robust control without the need for continually online training [7-10]. Hence, in this paper, an optimal Auxiliary Transient Neuro-Controller (ATNC) is developed for the GCSC to damp the transient oscillations in the power flow through the GCSC. The development was done in real-time environment using Real-Time Digital Simulator (RTDS) and TMS3206701 DSP.

II. GATE-CONTROLLED SERIES CAPACITOR

A. Principle of Operation

The GCSC is composed of two sets of anti-parallel GTOs and a capacitor bank in series with the transmission line for each phase , no additional reactor is needed in contrast with the TCSC as shown in Fig. 1a and 1b. If the GTOs are turned on all the time then the capacitor is by-passed and it does not provide any compensation. However, if the GTO's are turned off once per cycle at a determined blocking angle of γ, the capacitor in series with the transmission line turns on and off alternately and a voltage Vc appears across the capacitor. The

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The support from the National Science Foundation under the NSF CAREER Grant No: ECS # 0348221 and NSF Grant ECS # 0524183 are gratefully acknowledged by the authors.

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GCSC has a great advantage over TCSC. The blocking angle γ can be varied continuously which varies the fundamental components of V_c, whereas TCSC firing angle is discontinuous due to the zone in which a parallel resonance occurs between the Thyristor Controlled Reactor (TCR) and the capacitor [1-3]. In the GCSC, a blocking angle of 90 degree means that the capacitor is fully inserted and a blocking angle of 180 degree means that the capacitor is fully by-passed making the fundamental impedance of effective capacitive reactance to zero.

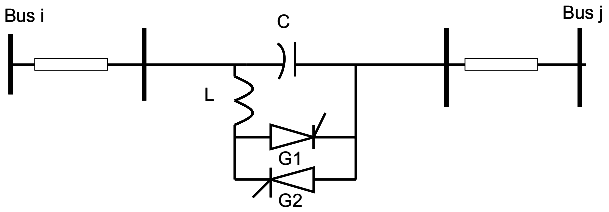

Fig. 1a Thyristor Controlled Series Compensator inserted in a transmission line.

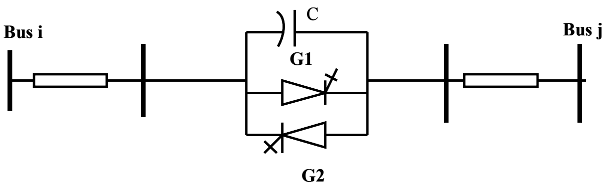

Fig. 1b Gate Controlled Series Capacitor inserted in a transmission line.

The harmonic analysis of the voltage waveform in the GCSC has been discussed in detail in [3]. The multi-modular form of GCSC has also been proposed in [3] to reduce the total harmonic distortion. Harmonic analysis is beyond the scope of this paper. The GCSC model designed in this paper is simple single pulse single module. The relationship between the compensating reactance and the GCSC blocking angle (α) is highly nonlinear as in (1). Hence, a nonlinear controller performs better during transients than the conventional linear controllers for the GCSC. The paper presents a neural network based auxiliary nonlinear controller to overcome the problem caused by this nonlinearity.

$$X_{ceff}(\alpha) = \frac{X_C}{\pi}\left[2\alpha - 2\pi - \sin 2\alpha\right] \tag{1}$$

B. Prospective Applications

The GCSC could be used in applications where either fixed capacitive compensation or a TCSC is used today, mainly to control power flow. The GCSC can operate in open loop to control the capacitive reactance added in series with the transmission line. It can also operate in closed loop where it controls the real power flow in the transmission line or maintain a constant compensation voltage. Power oscillation damping is also attainable with the GCSC.

III. OPTIMAL AUXILIARY TRANSIENT NEUROCONTROL

This work is an effort to implement an HDP based optimal ATNC for the GCSC. The auxiliary transient control architecture is shown in Fig. 2. The change in blocking angle (*Δα*) obtained from the HDP ATNC is added to the steady-state value of α_0 to generate the final blocking angle during disturbances or sudden changes in operating conditions. The steady-state blocking angle is obtained using the relationship between line power, each side bus voltages, line reactance (X_l) and the effective capacitive compensation (X_{ceff}) given by (1-2).

$$X_{ceff} = X_l - \frac{V_i V_j \sin(\theta_i - \theta_j)}{P_{lref}} \tag{2}$$

The steady-state blocking angle is then obtained from the inverse relationship in (1) through a function approximator or a lookup table.

The control structure consists of three different neural networks namely – *neuroidentifier, neurocontroller* and *critic.* The neuroidentifier is used to provide one step ahead prediction for the controlled variables of the dynamic power system. The neurocontroller is referred to as the action network. The critic network criticizes the action of the controller and approximates the cost-to-go function in the Bellman's equation (3) of dynamic programming.

$$J(t) = \sum_{k=1}^{\infty} \gamma^k U(t+k) \tag{3}$$

The HDP control design is shown in Fig 3. Though the underline technique remains same, the selection of parameters for the training of the HDP critic and action/controller depends on the applications to be used. The value of the discount factor (γ) and the choice of the utility function is critical for design of an optimal controller.

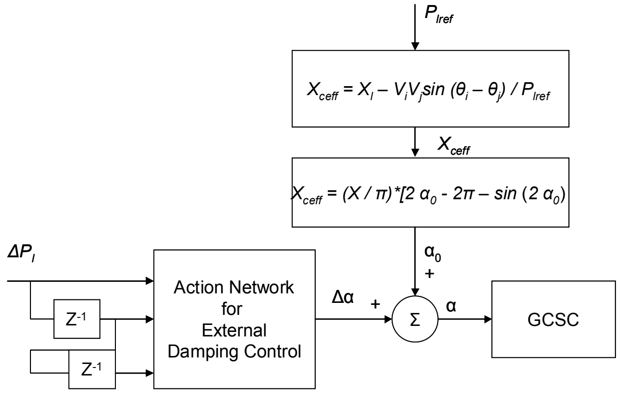

Fig. 2 Auxiliary transient neuro-control scheme employed for the GCSC.

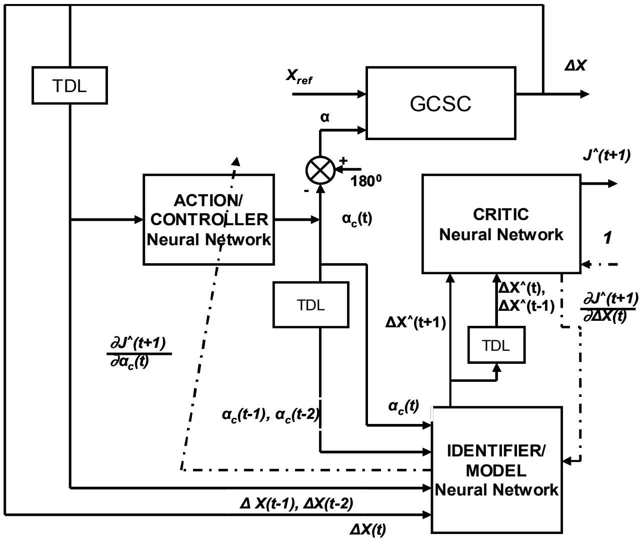

Fig. 3 HDP control architecture for ATNC.

The neurocontroller is developed in three steps namely – the neuroidentifier training, critic network training and the action network training. The neuroidentifier is made of 7 linear input neurons, 15 hidden sigmoidal neurons and 1 linear output neuron. The neuroidentifier training involves two phases, one with forced perturbations applied at a specified nominal operating point ($\alpha = 135^0$) for the GCSC using pseudorandom binary signals (PRBS) of magnitude $\pm 30^0$ in the range of 0.1 to 0.5 Hz and the other phase is training with natural disturbances such as line outages. The controlled variable is sampled at 100 Hz to provide the inputs to the neuroidentifier. The training procedure detailed in [7-9] is used for the critic and the action network training at different operating points and conditions until the weights of the networks do not change significantly. The action network is a MLP with 4 input linear neurons, 10 sigmoidal hidden neurons and 1 output linear neuron. The inputs to the action network are the power deviation signal (ΔP_l) and its two delayed values. The critic network is a feedforward MLP with 4 input linear neurons, 8 hidden sigmoidal neurons and 1 output linear neuron. The utility function $U(t)$ given in (4) is chosen to provide stable feedback for the optimal controller development [9].

$$U(t)=0.4*(\Delta P_l(t))^2 + 0.4*(\Delta P_l(t-1))^2 + 1.6*(\Delta P_l(t-2))^2 \qquad (4)$$

The initial weights of the action network can be obtained by cloning the existing PI controller or using the indirect adaptive control scheme [9] during pre-training. The pre-training is performed when the controller output is not fed to the system. This open loop training is done to get a suboptimal control signal from the controller. After pre-training of the neurocontroller, the control of the GCSC is switched to the neurocontroller. PRBS forced training signals (similar to those used for identifier training) is added to the power line reference to train the critic and action networks. The critic and action training is interleaved. Once the action network weights have converged for a number of operating conditions and points, the weights are fixed and neurocontroller is tested for different conditions.

IV. MULTI-MACHINE POWER SYSTEM

In spite of being a small test system, the two-area power system of Fig. 4 exhibit inter-area oscillations between two areas of the power systems [13-14]. The two-area system (shown in Fig. 4 with the proposed control method) consists of two fully symmetrical areas linked together by two transmission lines. The GCSC has been placed in one of the two parallel transmission lines between buses 7 and 8. Each area is equipped with two identical synchronous generators rated 20 kV/900 MVA. All the generators are equipped with identical speed governors and turbines, and exciters and AVRs. Loads are represented as constant impedances and split between the areas in such a way that area 1 is transferring about 413 MW to area 2. Three electro-mechanical modes of oscillation are present in this system; two inter-plant modes, one in each area, and one inter-area low frequency mode, in which the generating units in one area oscillate against those in the other area. The parameters of the system are given in the appendix. The two-area power system is simulated on the real-time digital power system [11].

V. REAL-TIME IMPLEMENTATION PLATFORM

Due to the complexity and expensive nature of the power system, it is very difficult to test new control schemes and algorithms on the real world power system. The proposed external damping controller is implemented on a digital signal processor (DSP) and its performance is tested on the two-area power system which is simulated on a real-time power system simulation platform, the RTDS®. The RTDS is a fully digital power system simulator capable of continuous real time operation. It performs electromagnetic transient power system simulations with a typical time step of 50 microseconds utilizing a combination of custom software and hardware.

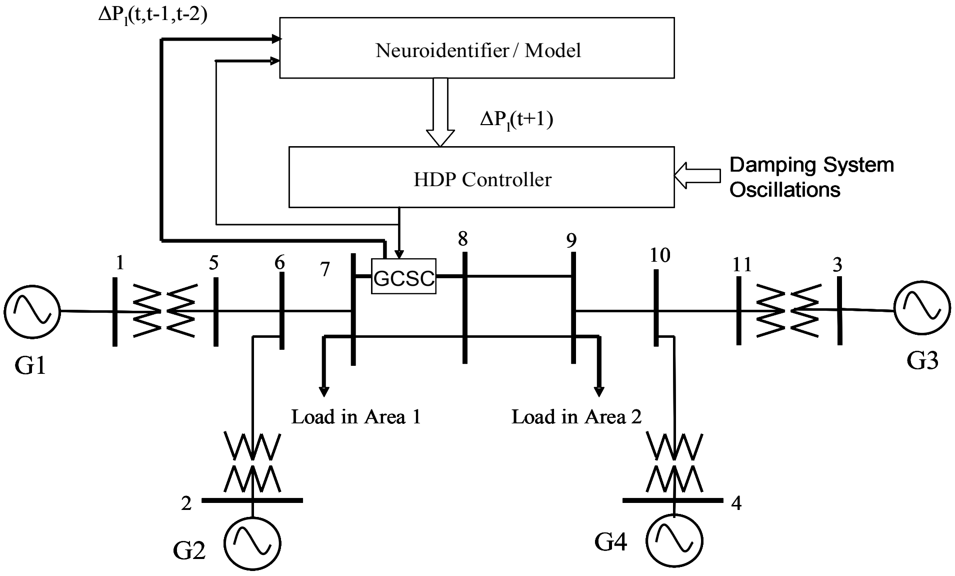

Fig. 4 Two area power system with GCSC and a HDP based ATNC.

The proprietary operating system used by the RTDS guarantees "hard real time" during all simulations [11]. It is an ideal tool for the design, development and testing of power system protection and control schemes. With a large capacity for both digital and analogue signal exchange (through numerous dedicated, high speed I/O ports), physical protection and control devices are connected to the simulator to interact with the simulated power system.

The RTDS software is divided into two main categories, namely the graphical user interface and the underlying solution algorithms for network equations and component models. All aspects of the simulator operation, from drafting the simulation network to recording simulation results, are controlled through the user friendly graphical interface RSCAD. RSCAD was developed to address practical issues encountered when performing real time simulation studies. There are two main RSCAD modules, the Draft and the Run Time. The Draft software module is used for circuit assembly and parameter entry. The window is divided into two, with the circuit assembly area on the left, and the library window on the right. The Run Time software module is used to control the operation RTDS simulator. Through the Run Time, the user performs actions such as the starting and stopping of simulation cases, initiating system disturbances, changing system set points, on-line monitoring of system quantities, triggering data acquisition and transient fault recordings as well as many other operator/control functions. Report ready plots can also be printed directly from the Run Time.

The damping controller consisting of the neuroidentifier and the neurocontroller is implemented on the Innovative Integration M67 DSP card (based on the TMS3206701 processor), operating at 160 MHz, hosted on a Pentium III 433 MHz personal computer. The M67 DSP card is equipped with two A4D4 modules [12]. Each A4D4 module is equipped with four analog-to- digital (A/D) converters and four digital-to-analog (D/A) converters. The DSP (implements external damping controller) and RTDS® (implements power system) interface and laboratory hardware setup is shown in Figs. 5 and 6 respectively. For the controller development, a sampling frequency of 100 Hz (period of 10 ms) is used.

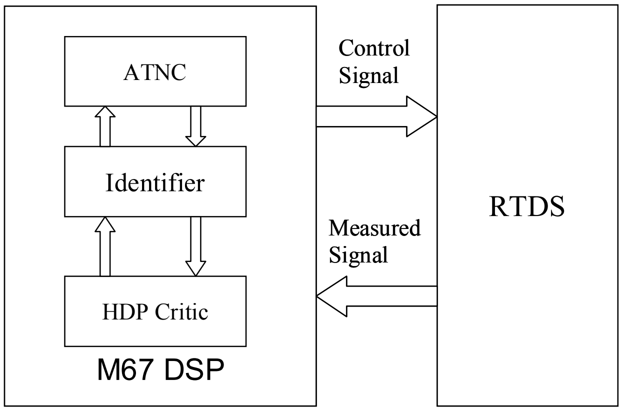

Fig. 5 Block diagram of the M67 DSP (WACS) and the RTDS® interface.

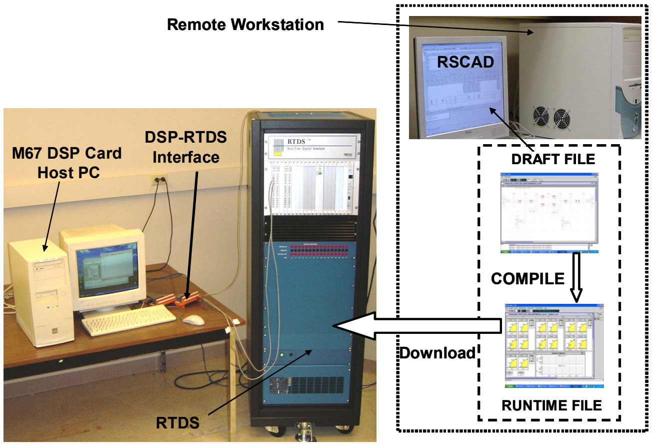

Fig. 6 Laboratory hardware setup with the RTDS®.

VI. RESULTS AND DISCUSSIONS

The system is built in RTDS and the controller is developed in the TMS3206701 DSP which is connected to the GCSC firing circuit through analog channels of the DSP. Different disturbance tests are carried out to investigate the performance of the optimal ATNC. Figs. 7 and 8 show the performance of the active and reactive power flow through the GCSC with and without ATNC when one transmission line between buses 8-9 is taken out for 200 ms. The power flow oscillation damps out much quicker with ATNC than with the conventional PI controller. The control signal provided by ATNC during the disturbance is shown in Fig. 9.

In another test, the load at bus 9 is increased by 5% and the corresponding active and reactive power flow, and control signal provided by the ATNC are shown in Figs. 10, 11 and 12 respectively. Again, the GCSC controlled by the ATNC shows improved transient performance.

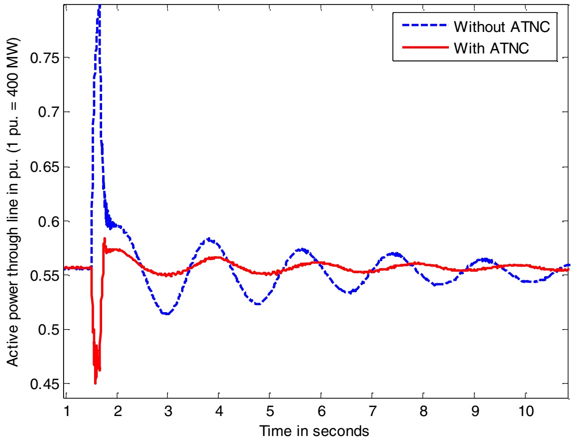

Fig. 7 Active power flow through the GCSC during line 8-9 outage for 200 ms.

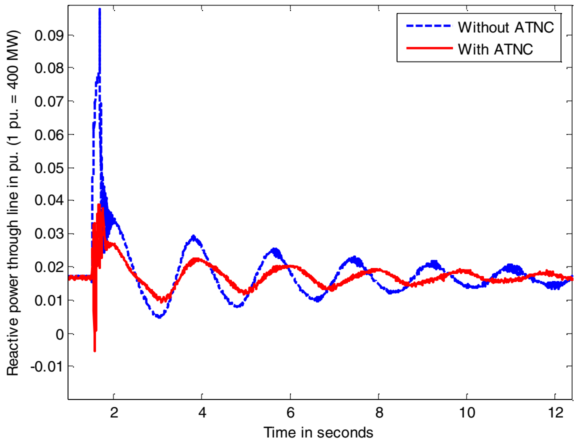

Fig. 8 Reactive power flow through GCSC during line 8-9 outage for 200 ms.

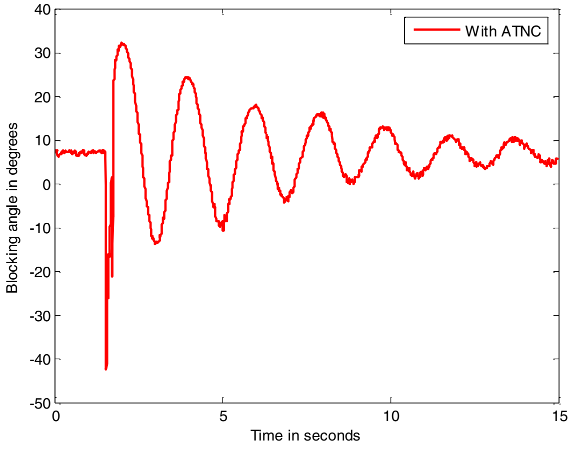

Fig. 9 Control signal provided by the ATNC during the line outage.

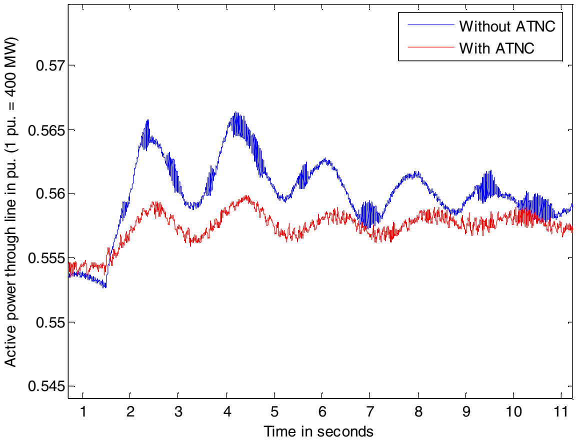

Fig. 10 Active power flow through GCSC for a load change.

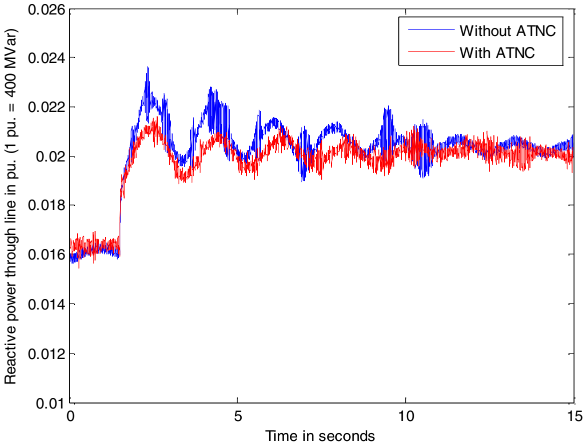

Fig. 11 Reactive power flow through GCSC for a load change.

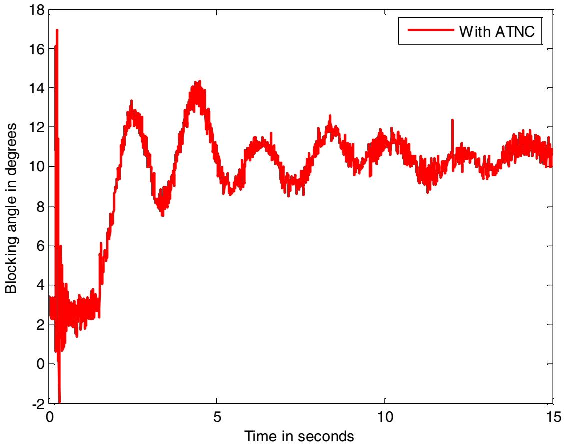

Fig. 12 Control signal provided by the ATNC for a load change.

VII. CONCLUSION

An optimal auxiliary transient neurocontroller has been developed for a new type of FACTS device and implemented in real-time using RTDS and DSP platform. The ATNC compensates for the highly nonlinear characteristic of the effective reactance and the GCSC control signal (blocking angle) during transients. The effectiveness of the HDP design has been exploited to develop an optimal ATNC for the GCSC. The real-time implementation results show significant improvement in the damping of transient oscillations in the line flows and the feasibility of the ATNC for real world GCSC applications. Future investigations remain to be tried out on large power systems.

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