Damping Of Low Frequency Power Oscillations and Transient Stability Enhancement by Using Auxiliary Fuzzy Logic Based Static Synchronous Series Compensator

G.N.L.Sravani *, Dr.M.Sridhar **

*(Department of Electrical and Electronics Engineering, GIER, JNTU University, Kakinada)

** (Department of Electrical and Electronics Engineering, GIER, JNTU University, Kakinada)

Abstract

*Low Frequency Oscillations (LFO) occur in power systems because of lack of the damping torque .Low frequency oscillations (LFO) are a frequent adverse phenomenon which increase the risk of instability for the power system and thus reduce the total and available transfer capability (TT C and ATC). This brief investigates the damping performance of the static synchronous series compensator (SSSC) equipped with an auxiliary fuzzy logic controller (FLC). At the outset, a modified Heffron-Phillips model of a single machine infinite bus (SMIB) system installed with SSSC is established. In the following an auxiliary FLC for SSSC is well-designed to enhance the transient stability of the power system. In order to evaluate the performance of the proposed FLC in damping LFO, the SMIB power system is subjected to a disturbance such as changes in mechanical power. Simulation results Show that the developed FLC would be more effective in damping electromechanical oscillations in comparison with the conventional proportional-integral (PI) controller.***

Keywords: *Low frequency oscillations (LFO), static synchronous series compensator (SSSC), single machine infinite bus (SMIB) power system, Heffron-Phillips model, fuzzy logic damping controller.*

I INTRODUCTION

Power systems are among the largest, most complex systems made by human beings. They exhibit various modes of oscillations due to interaction among system components. By interconnecting the large power systems, utilities have achieved more reliability and economical viability. However, low frequency oscillations (LFO) with the frequencies in the range of 0.2 to 2 Hz are one of the direct results of the large interconnected power systems. The power oscillations may come up to entire rating of a transmission line, as they are superimposed on steady state line flow. Hence, these oscillations would limit the total and available transfer capability (TTC and ATC) by requiring higher safety margins. These electromechanical modes of oscillations are usually poorly damped which may increase the risk of instability of power system. Thus, it is urgent and important to damp the electromechanical oscillations as soon as possible [1] in order to maintain the stability of the entire system.

To mitigate the oscillations in the power system many different methods have been proposed .For many years, power system stabilizer (PSS) has been one of the traditionally devices used to damp out the oscillations [2]. It is reported that during some operating conditions, PSS may not mitigate the oscillations effectively. However, there have been problems experienced with PSSs over the years of operation. Some of these were due to the limited capability of PSS, in damping only local and not interarea modes of oscillations. In addition, PSSs can cause great variations in the voltage profile under severe disturbances and they may even result in leading power factor operation and losing system stability [3]. Hence, other effective alternatives are required in addition to PSSs [4]. This situation has necessitated a review of the traditional power system concepts and practices to achieve a larger stability margin, greater operating flexibility, and better utilization of existing power systems.

The Benefits of Flexible AC Transmission Systems (FACTs) usages to improve power systems stability are well known [5], [6]. The growth of the demand for electrical energy leads to loading the transmission system near their limits. Thus, the occurrence of the LFO has increased. FACTs Controllers has capability to control network conditions quickly and this feature of FACTs can be used to improve power system stability.On the other hand, the advent of flexible ac transmission system (FACTS) devices has led to a new and more versatile approach to control the power system in a desired way . FACTS controllers provide a set of interesting capabilities such as power flow control, reactive power compensation, voltage regulation, damping of oscillations, transient stability enhancement and so forth [7]-[14]. The static synchronous series compensator (SSSC) is one of the series FACTS devices based on a solid-state voltage source inverter which generates a controllable ac voltage in quadrature with the line current [15]. By this way, the SSSC emulates as an inductive or capacitive reactance and hence controls the power flow in the transmission lines. In [16], authors have developed the damping function for the SSSC. It is a well-known fact that by properly designing an auxiliary power oscillation damping (POD) controller, the SSSC would be capable of suppressing the fluctuations as an ancillary duty [16].

Different methods have been proposed in the literature to design a POD controller for SSSC. For example, in [16] authors have used the phase compensation method to develop a supplementary damping controller for SSSC. The main problem associated with these methods is that the control process is based on the linearized machine model. The other frequently used approach is the proportional-integral (PI) controller. Although the PI controllers offer simplicity and ease of design, their performance deteriorates when the system conditions vary widely or large disturbances occur [17]-[18]. In this context, some new stabilizing control solutions for power system have been presented. Recently, fuzzy logic controllers (FLCs) have emerged as an efficient tool to circumvent these drawbacks.

The qualitative and quantitative knowledge about the system operation through some hierarchy is integrated by FLC. Fuzzy logic provides a general concept for description and measurement of systems. Most of fuzzy logic systems encode human reasoning into a program in order to arrive at decisions or to control a system [19]-[20]. Fuzzy logic comprises fuzzy sets, which is a way of representing non-statistical uncertainty along with approximate reasoning and in fact includes the operations used to make inferences [21]. There are some manuscripts which have demonstrated the successful application of FLC for transient stability enhancement of a power system. In [22], Limyingcharone *et al.* have used a fuzzy supplementary controller with the aim of achieving low frequency oscillations damping

The investigation is carried out for a single machine infinite bus (SMIB) power system installed with a SSSC. In the sequel, the linearized Heffron-Phillips model [23] of the examined plant is evolved. An auxiliary FLC is utilized to modulate the amplitude modulation index during the transients to enhance the stability of the power system. Subsequently, aiming to provide a fruitful investigation, a comparative study is developed where the FLC is compared with a conventional PI controller. Simulation results using MATLAB/Simulink exhibits the superior damping of LFO obtained with FLC than PI controller.

II. POWER SYSTEM MODELING

The linearized Phillips-Heffron model of a power system installed with SSSC is used to investigate the impact of SSSC on damping oscillations in power systems. This section is dedicated to extract an exact linearized Heffron-Phillips model for the investigated power system. As depicted in Fig. 1, a single machine infinite bus (SMIB) system installed with SSSC is considered as the sample power system. In this figure, XT is the transformer reactance and XL corresponds to the reactance of the transmission line. Also, Vt and Vb represent the generator terminal voltage and infinite bus voltage respectively. A simple SSSC consisting of a three-phase GTO-based voltage source converter (VSC) is incorporated in the transmission line. It is assumed that the SSSC performance is based on the well-known pulse width modulation (PWM) technique. For the SSSC, $_{\text{XSCT}}$ is the transformer leakage reactance; $_{\text{VINV}}$ is the series injected voltage; CDC is the DC link capacitor; VDC is the voltage at DC link; m is amplitude modulation index and ø is the phase angle of the series injected voltage.

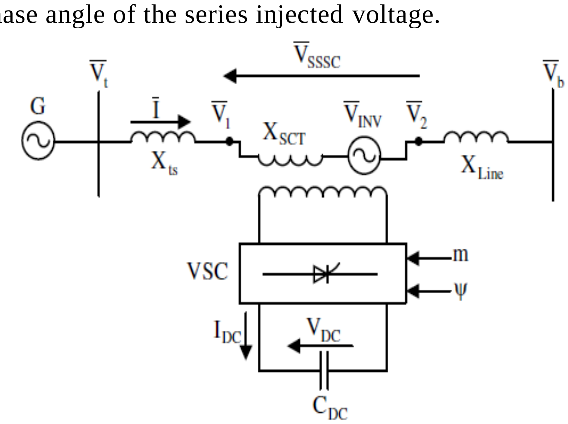


Fig. 1 A single machine infinite bus power system with a SSSC

2.1. Nonlinear Dynamic Model of the Power System with SSSC

As the first step, a nonlinear dynamic model forthe examined system is derived by neglecting the resistance of all the components including generator, transformer, transmission line, and series converter ansformer. The equations specifying the dynamic performance of the SSSC can be written as follows [16].

$$\bar{I} = I_d + jI_q = I\angle\varphi$$

$$\overline{V}_{INV} = mkV_{DC}(cos\psi + j\,sin\psi) = mkV_{DC}\angle\psi\,,$$
$$\psi = \varphi \pm 90$$
$$\frac{dV_{DC}}{dt} = \frac{mk}{C_{DC}}(I_d\,cos\psi + I_q\,sin\psi) \qquad (1)$$

Where k is the fixed ratio between the converter AC and DC voltages and is dependent on the inverter structure. For a simple three-phase voltage source converter k is equal with 3/***4 [5].*** Most of the times, SSSC performs as a pure capacitor or inductor; hence, the only main controllable parameter for SSSC is the amplitude modulation index *m*.

For the work at hand, the IEEE Type-ST1A excitation system is considered. Fig.2 displays the block diagram of the excitation system where the terminal voltage Vt and the reference voltage V_{ref} are the input signals. KA and TA are the gain and time constant of the excitation system respectively.

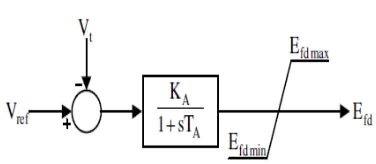


Fig. 2 IEEE Type-ST1A excitation system

The dynamic model of the power system in Fig. 1 would be as follows [24].

$$\dot{\delta} = \omega_0(\omega - 1) \qquad (2)$$
$$\dot{\omega} = \frac{P_m - P_e - P_D}{M} \qquad (3)$$
$$\dot{E}'q = \frac{(-E_q + E_{fd})}{T'_{do}} \qquad (4)$$
$$\dot{E}_{fd} = \frac{-E_{fd} + K_A(V_{ref} - V_t)}{T_A} \qquad (5)$$
$$\dot{V}_{DC} = \frac{3m}{4C_{DC}}(I_d\,cos\psi + I_q\,sin\psi) \qquad (6)$$

where

δ : Rotor angle of synchronous generator in radians

Ù : Rotor speed in rad/sec

Pm : Mechanical power input to the generator

Pe : Electrical power of the generator

PD = *D*(ù -1),

D : Damping coefficient

*E*q1 : Generator internal voltage

E_{fd}: Generator field voltage

Id : d-axis current

Iq : q-axis current

2.2. Linear Dynamic Model of the Power System with SSSC

The linear heffron-Philips model of an SMIB system including SSSC can be extracted by linearizing the nonlinear model around a nominal operating point [16].

$$\Delta\dot{\delta} = \omega_0\Delta\omega \qquad (7)$$
$$\Delta\dot{\omega} = \frac{(\Delta P_m - \Delta P_e - D\Delta\omega)}{M} \qquad (8)$$
$$\Delta\dot{E}'_q = \frac{(-\Delta E_q + \Delta E_{fd})}{T'_{do}} \qquad (9)$$
$$\Delta\dot{E}_{fd} = \frac{-\Delta E_{fd} + K_A(\Delta V_{ref} - \Delta V_t)}{T_A} \qquad (10)$$
$$\Delta\dot{V}_{DC} = K_7\Delta\delta + K_8\Delta E'q + K_9\Delta V_{DC} + K_{DCm}\Delta m \qquad (11)$$

Where

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E'q + K_{pDC}\Delta V_{DC} + K_{pm}\Delta m \qquad (12)$$
$$\Delta E_q = K_4\Delta\delta + K_3\Delta E'q + K_{qDC}\Delta V_{DC} + K_{qm}\Delta m \qquad (13)$$
$$\Delta V_t = K_5\Delta\delta + K_6\Delta E'q + K_{vDC}\Delta V_{DC} + K_{vm}\Delta m \qquad (14)$$

Fig. 3 exhibits the transfer function model for the modified Heffron-Phillips model of the SMIB system with SSSC

2.3.State Space Representation of Linear Model

The modified Heffron-Phillips model can be represented in state-space as:

$X = AX + BU$

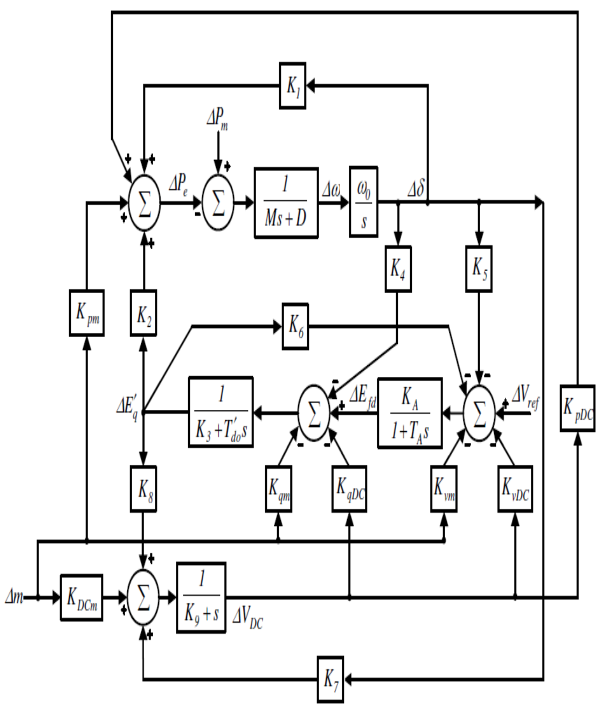


Fig. 3 Heffron-Phillips model of the single machine infinite Bus power system with SSSC

Where X and U are defined as the state control vector respectively.

$$X = [\,\Delta\delta \quad \Delta\omega \quad \Delta E'q \quad \Delta E_{fd} \quad \Delta V_{DC}\,]^T \tag{16}$$

$$U = [\,\Delta m\,] \tag{17}$$

With respect to (9)-(17), the corresponding system matrix namely A,and the control matrix B,are obtained for the investigated powersystem.

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pDC}}{M} \\ -\frac{K4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} & \frac{-k_{qDC}}{T'_{do}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vDC}}{T_A} \\ K7 & 0 & K8 & 0 & K9 \end{bmatrix} \tag{18}$$

The nominal operating point for the power system is set to the given values.

$$B = \begin{bmatrix} 0 \\ -K_{pm} \\ -K_{qm} \\ -K_{vm} \\ K_{DCm} \end{bmatrix} \tag{19}$$

2.4. Calculation of the Heffron-Phillips Model

Constants

Pe = 0.8pu, Qe =0.144pu, Vb = 1pu

The Heffron-Phillips model constants are calculated based on the given values for the nominal operating point and some other data which are reported in the Appendix A. Also the parameters of SSSC are given in the Appendix B. Eventually; Appendix C gathers all of the constants computed for the system model depicted in Fig. 3.

III. DESIGN OF DAMPING CONTROLLERS

Aiming to damp the low frequency oscillations, two sorts of damping controllers are designed and compared with each other. In the investigated system, as mentioned earlier, the SSSC series converter amplitude modulation index namely *m*, provides a control signal to yield better damping of oscillations[1]. In the subsequent sections, each controller is individually discussed in detail

3.1 Conventional Proportional-Integral (PI) Controller

The damping controllers are designed so as to provide an extra electrical torque in phase with the speed deviation in order to enhance the damping of oscillations [1]. Fig. 4 shows the conventional PI controller structure. With respect to this figure, it can be observed that the first block compares the generator rotor speed with the reference speed. In the sequel, the error is fed to a PI controller to generate the proper amplitude modulation index for the SSSC converter. There are different methods to design PI controllers such as try and error method, pole-placement, Ziegler-Nichols and so forth. In this survey, try and error method is used to set suitable values for PI controller gains.

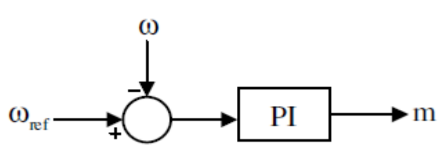


Fig. 4 Conventional PI damping controller

3.2.Auxiliary Fuzzy Logic Damping Controller

As explained in the preceding sections, although the PI controllers offer simplicity and ease of design, their performance deteriorates when the system conditions vary widely or large disturbances occur. Consequently, to ensure the effective performance of damping controller over wide range of system operations and also to increase the transient stability of the system, a supplementary fuzzy logic controller (FLC) based on the Mamdani's fuzzy inference method is designed for the SSSC input. FLC generates the required small change for amplitude modulation index to control the magnitude of the injected voltage. The centroid defuzzyfication technique was used in this fuzzy controller.

Fig. 5 demonstrates the FLC structure. In this case, a two–input, one–output FLC is considered. The input signals are angular velocity deviation *($\Delta\omega$)* and load angle deviation *($\Delta\delta$)* and the resultant output signal is the amplitude modulation index *(Äm)* for SSSC converter.

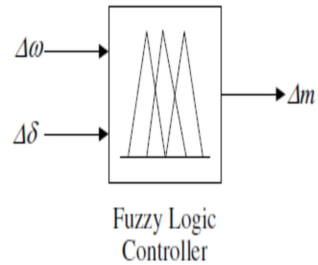


Fig. 5 Fuzzy logic damping controller structure

The presented FLC has a very simple structure.

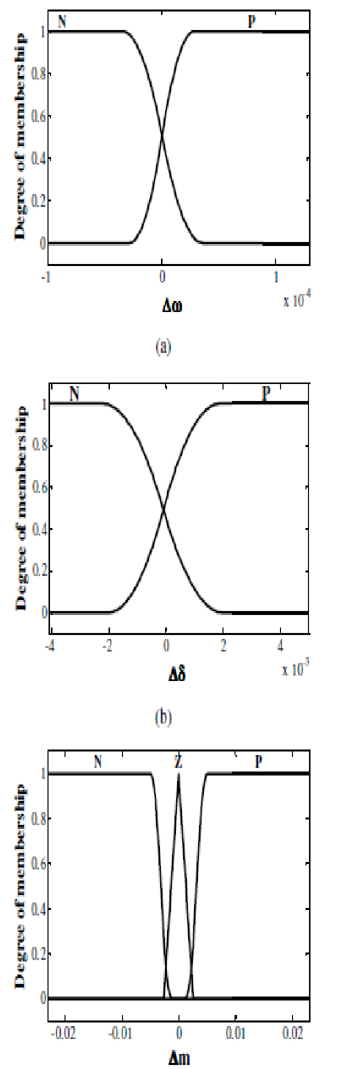


Fig. 6 (a), (b) inputs membership function, (c) output membership function

The membership functions of the input and output signals are shown in Fig. 6. There are two linguistic variable for each input variable, including, "Positive" (P), and "Negative" (N). On the other hand, for the output variable there are three linguistic variables, namely, "Positive" (P), "Zero" (Z), and "Negative" (N).

The rules used for the FLC are chosen as follows:

If Δω is P **and** Δδ is P, **then** Δ*m* is P.
If Δω is P **and** Δδ is N, **then** Δ*m* is Z.
If Δω is N **and** Δδ is P, **then** Δ*m* is Z.
If Δω is N **and** Δδ is N, **then** Δ*m* is N.

Fig. 7 demonstrates the output of fuzzy controller versus its inputs. As it can be seen in Fig. 7, the rules surface is smooth which is a desirable option in design procedure.

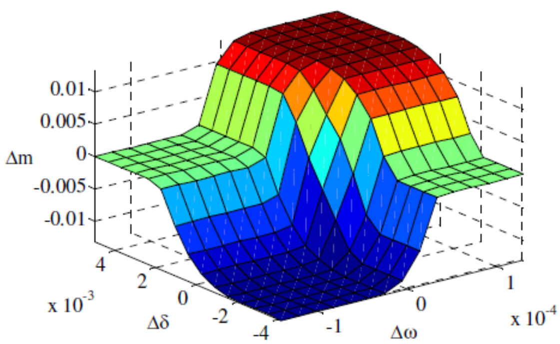
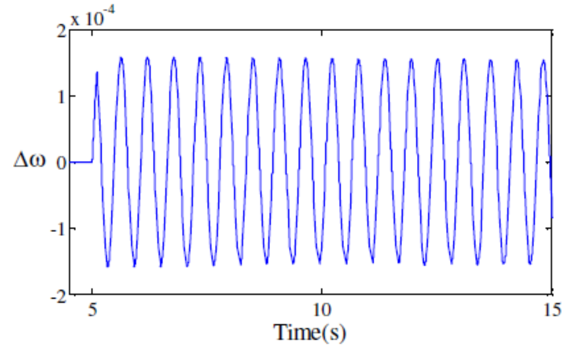


Fig. 7 The rules surface for *m* controller

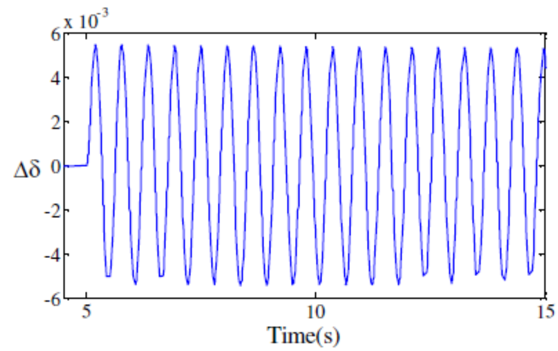
IV. SIMULATION RESULTS AND DISCUSSION

In order to compare the proposed fuzzy logic damping controller performance with the conventional PI damping controller, some useful simulations are provided. The contingency simulated is a step change in mechanical power *(Δ Pm = 0.01)* which occurs at t=5sec and lasts for 0.1 sec.

At the beginning, the SSSC has no damping controller. For this case, the angular velocity deviation and also the load angle deviation responses are displayed in Fig. 8. This figure reveals that when there is no damping controller, the LFO damping is very poor; hence an auxiliary damping controller is essentially required to improve the transient stability of the system.



(a)



(b)

Fig. 8 (a), (b) Low frequency oscillations of power system with no damping controller

In the second case, simulations are performed with the same contingency in mechanical power but the SSSC has been equipped with a damping controller. Simulation results are shown in Fig. 9. With respect to this figure, it is deduced that the fuzzy logic controller exhibits better damping than the conventional PI controller. Likewise, the power system transient stability is increased when the SSSC is equipped with the fuzzy logic damping controller. Simulation results validate the efficiency of the proposed fuzzy logic damping controller and its better performance is emphasized.

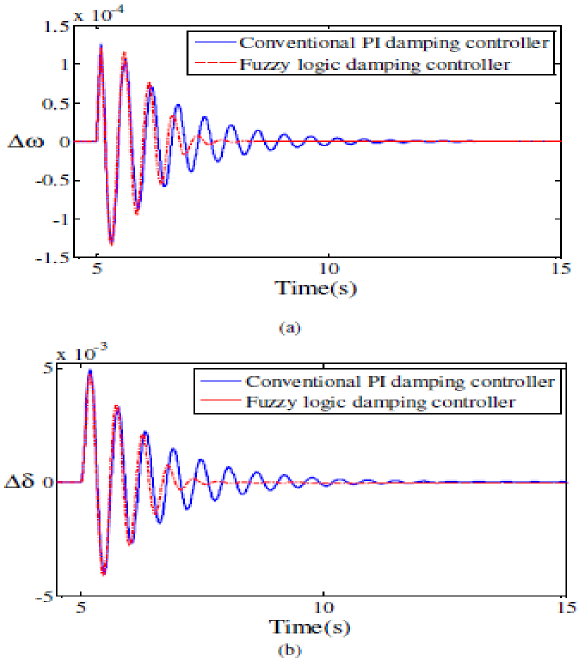


Fig. 9 (a), (b) Comparison of conventional PI and fuzzy logic controllers in Low frequency oscillations damping

V.CONCLUSION

This manuscript serves an exact investigation to obtain a complete linearized Heffron-Phillips model for a single machine infinite bus power system equipped with an SSSC to study LFO damping with an auxiliary FLC. It was shown that a contingency in power system will cause to initiate power oscillations. In the sequel, two types of controllers, namely, the conventional PI and the FLC were designed to damp the system oscillations. A comparative study between the FLC and PI controller shows that the proposed FLC has superior performance and influence in transient stability enhancement and oscillations damping. Simulation results validate the efficiency of the proposed fuzzy logic damping controller and its better performance is emphasized. Consequently, the fuzzy logic controller would be a better option in the design of damping controllers.

APPENDIX A
POWER SYSTEM PARAMETERS
Generator:
M=2H=6 MJ/MVA, D=0
T'do=5.044 s
Xd=0.1 pu, Xq=0.06 pu, X'd=0.025 pu
f0=60 Hz, ω0=2πfo
Excitation system:
KA=5, TA=0.005 s
Transmission line and transformer reactances:
XLine=0.2 pu, Xts=0.2 pu

APPENDIX B
THE SSSC PARAMETERS
CDC=1 pu; VDC=0.5 pu; m=0.15; XSCT=0.1 pu

APPENDIX C
HEFFRON-PHILLIPS MODEL CONSTANTS
*K*1=1.9014; *K*2=0.6735; *K*3=1. 1429
*K*4=0.0498; *K*5=-0.0127; *K*6=0. 9517
*K*7=-0.1759; *K*8=0.0302; *K*9= 1.402×10-4
*K*DCm=-0.4255;*K*pDC=0.0244; *K*qDC=0.0106;
*K*vDC= -0.0035,*K*pm=0.0839;
*K*qm=0.0354; *K*vm=-0.008

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