Fuzzy Controlled SMES Unit for Power System Application

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Abstract:

This paper presents a new approach to control Superconducting Magnetic Energy Storage (SMES) unit for power system application. The SMES unit is used to improve the dynamic performance of P-f and Q-V loops of a power system. Two independent fuzzy controllers are assigned, one for the frequency control and another for the voltage control. Speed deviation ($\Delta\omega$) and acceleration ($\Delta\dot{\omega}$) of a synchronous generator are taken as the input signals to the Fuzzy Frequency Controller (FFC). The terminal voltage deviation (ΔV_t) and its derivative ($\Delta\dot{V}_t$) are considered as the inputs to the Fuzzy Voltage Controller (FVC). To get the maximum benefit from the SMES unit, a supplementary control is generated by using the output of FFC and the inductor current deviation (ΔI_{sm}) as inputs. ΔI_{sm} is also used as a negative feedback signal to ensure the SMES energy is restored to its predisturbance level. The desired P-modulation from the SMES is obtained by adding this supplementary control signal to the output of FFC while the output of the FVC is the desired Q-modulation. The effective use of the SMES unit is verified for small as well as large disturbances for a single machine infinite bus system, and simulation results are presented and discussed.

1. Introduction:

In recent years constraints imposed by environment, right of way and energy costs have resulted in power systems operating with considerably reduced stability margins. As a result, modern power systems rely heavily on stabilizing devices to maintain reliable and stable operation [1]. These devices should provide adequate damping in the system, during the transient period following a system disturbance, such as line switching, load changes and fault clearance. To prevent collapse of the system due to loss of synchronism or voltage instability, countermeasures such as power system stabilizers, optimal turbine governor control systems and phase shifters have been used.

Recently it has been shown that energy storage devices such the SMES unit can also be used as a stabilizer for power systems[2-3]. Due to the rapid advances in Superconductive technology, such units of reasonable size have been designed and commissioned successfully. By effective control of the GTO thyristors, these units they can be made to operate both as a source or sink of active and reactive power, to suit the system requirements[4].

However, the effective use of SMES unit greatly depends on its control strategy. Many kinds of controllers for the SMES unit have been proposed in literature. [3-4]. The gain settings of SMES controllers are usually fixed at values which are determined based on nominal operating point[3]. These fixed gain controllers are always a compromise between the best setting for light and heavy load conditions. It is impossible for the SMES unit with these fixed gain controllers to maintain the best damping performance when there is a drastic change in system condition, such as that resulting from a three phase fault in power system. To solve this problem, a PI controller was proposed for the SMES unit in reference [4]. Based on the system eigenvaules, the controller parameters were determined to provide active power compensation to the power system. But there is no arrangement to bring the SMES energy storage capacity to its predisturbance level without which the SMES unit may not be able to respond for subsequent needs. In designing the PI controller, the Q-modulation of the SMES unit has not been considered. In practice, being an inductive device, SMES unit consumes reactive power. Also, voltage at the terminal of the generator changes drastically during a three-phase fault and adequate Q-compensation from the SMES unit will definitely help in restoring stability. Therefore, the effect of reactive power of the SMES unit must also be considered in the design of a SMES controller. As an alternative to these controls, the concept of fuzzy logic was first introduced by Zadeh[5], and this has been successfully applied to various control problems [6].

In the following sections a comprehensive control strategy is for the SMES unit is developed and the results of applying this to a test system are presented.

2. The Proposed Control Strategy

2.1 Configuration of the System

In this paper, the simple fuzzy logic controller proposed in [7], is modified to enhance the low frequency damping of the synchronous machine. In [7], a fuzzy logic control system for the SMES unit was proposed considering a small load perturbance at the load end of the transmission line of an isolated system. In the conventional FLC, the membership

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functions are supplied by an expert or tuned off-line. In the proposed fuzzy model, membership functions are generated at the very beginning, using sensed frequency and voltage signals.. The proposed fuzzy control algorithm will automatically generate the appropriate membership function. for any type of disturbance. To ensure the effective use of the SMES unit, a supplementary signal, generated from the FFC output and inductor current is used as explained in Section 3.2.

Fig. 1 shows the basic configuration of the SMES unit. It is connected to a power system shown in Fig. 2. The generator is equipped with an automatic voltage regulator (AVR). The governing system is of reheat heat turbine type[4]. The DC magnetic coil of the SMES unit is connected to the AC grid through a Power Conversion System (PCS) which includes an inverter/rectifier. Under disturbed conditions, the transfer of SMES energy is done almost immediately depending on the system requirement. As the governor and other control mechanisms start working to set the power system to the equilibrium condition, the SMES energy is returned to the predisturbance level . This is ensured by providing a suitable inductor current feedback to the SMES controller as shown in Fig. 3.

2.2 Fuzzy Controllers

The first step in designing a fuzzy controller is the proper choice signals for the controller input. Moreover, choosing the appropriate linguistic variables formulating the fuzzy control rules are also important factors in the performance of the fuzzy control system. Empirical knowledge and engineering intuition play an important role in choosing linguistic variables and their corresponding membership functions. Using the knowledge gained from experience, generator speed deviation($\Delta\omega$) and acceleration ($\Delta\dot{\omega}$) of the synchronous generator are chosen as the input signals to the fuzzy frequency controller(FFC). The terminal voltage deviation (ΔV_t) and its derivative ($\Delta\dot{V}_t$) are considered as the inputs to the fuzzy voltage controller(FVC). The acceleration signal can be derived from the speed signals measured at two successive sampling instants:

$$\Delta\dot{\omega}(kT_s) = \frac{\Delta\omega(kT_s) - \Delta\omega[(k-1)T_s]}{T_s}$$

where k is the sampling number and T_s is the sampling period. The voltage derivative is derived in a similar manner. After choosing proper variables as input and output of the fuzzy controller, it is required to decide on the linguistic variables. These variables transform the numerical values of the input of the fuzzy controller, to fuzzy quantities. The number of these linguistic variables specifies the quality of the control which can be achieved using the fuzzy controller. As the number of linguistic variables increases, the computational time and memory requirement increase. Basically, the sensitivity of the variable determine the number of fuzzy subsets. In this study, nine linguistic variables for each of the input and output variables are used. These are, VLP(very large positive), LP(large positive), MP(medium positive), SP(small positive), Z(zero), SN(small negative), MN(medium negative), LN(large negative) and VLN(very large negative). The minimum and maximum values of each of the input variables of FFC and FVC are generated on-line following the disturbance. Few samples of the input variable are required to arrive at the maximum and minimum limits which will be used in the respective membership function. The basic structure of the membership functions of the input variables used in the fuzzy control system are the same and is shown in Fig. 4. The fuzzy parameters C0, C1,........ are different for the different input variables and they are determined only when the SMES unit is activated for power compensation(sampling starts). The sampling period used in the study is 0 .001 second.

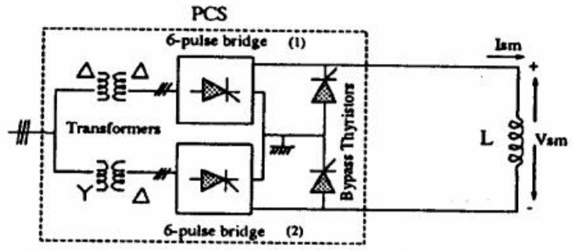

Fig. 1. The schematic diagram of the SMES unit

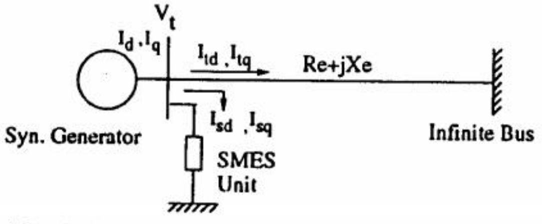

Fig. 2. The power system with SMES unit

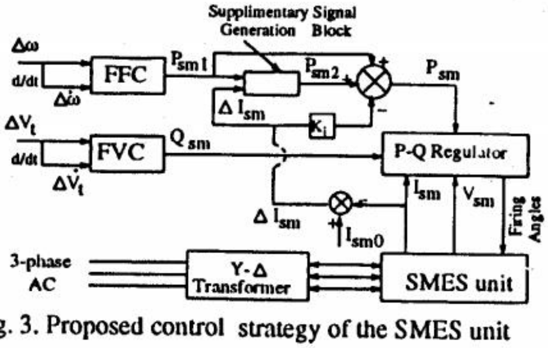

Fig. 3. Proposed control strategy of the SMES unit

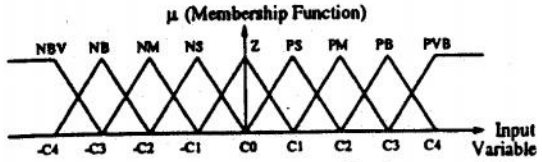

Fig. 4. Fuzzy membership function for input variable

The input variable pairs are:

1. Angular frequency deviation ($\Delta\omega$) and its derivative ($\Delta\dot{\omega}$) in p.u.
2. Terminal voltage deviation (ΔV_t) and its derivative ($\Delta\dot{V}_t$) in p.u. and
3. FFC output P_{sm1} in MW and inductor current deviation(ΔI_{sm}) in kA.

Note the above parameter values are depend on the type of the disturbance. The procedure of determination of the FFC parameters are as follows:

1. Sample $\omega(k)$ and $\omega_{ref}(k)$.
2. Compute $\Delta\omega(k)$.
3. Compute $\Delta\dot{\omega}$ (k)
4. Determine the maximum limit of $\Delta\dot{\omega}$.
   $C4_{\Delta\dot{\omega}} = |\Delta\dot{\omega}|$
5. Calculate other parameters (C0, C1 ....) from C4 for the same variable.
6. Decide the maximum value of the $\Delta\omega$ to be used in the corresponding membership function.

$$C4_{\Delta\omega} = K_W * |\Delta\dot{\omega}|$$

The constant K_W is selected intuitively depending on the type of the power system and the capacity of the SMES unit. Once the upper bound of the membership function is chosen, the others parameters can be calculated from this.

A similar method is used to determine the fuzzy voltage parameters. However, to determine the fuzzy parameters for the third input pair, one has to know the available maximum MVA of the SMES unit and the initial value of the inductor current. The upper bound of the input P_{sm1} (the output of FFC) is the maximum MW output from the SMES unit in the rectifier mode while lower bound is the maximum MW transfer to system in the inverter mode. Due to limitation of converter operation,

$$P_{sm,max}|(\text{rectifier}) > |P_{sm,max}|(\text{inverter})$$

From the upper and lower limits of the inductor current under continuous mode, the upper and lower bounds of ΔI_{sm} are calculated.

2.3 Inductor Current Feedback and Supplementary Control Signal:

It is desirable to restore the inductor current to its rated value as quickly as possible after a system disturbance, so that the SMES unit can respond properly to any subsequent disturbance. To achieve this, the inductor current deviation is sensed and used as negative feedback in the SMES control loop to achieve quick restoration of current and SMES energy level.

The active and reactive power capability of the SMES unit can be fully utilized if an adaptive control technique is used. However this is a complicated process and requires large computer memory. Another alternative is to generate a supplementary control signal for the P-modulation of the SMES unit. With the inductor current feedback and supplementary control, the desired P-modulation of the SMES unit can be obtained as

$$P_{sm} = P_{sm1} + P_{sm2} - K_i\ \Delta I_{sm}$$

where P_{sm2} is the output of the supplementary signal generation block and is explained in detail in section 2.5, and K_i is the gain of ΔI_{sm} feedback.

A similar method can be used to obtain the desired Q-modulation. But the execution time will be increased. Due to coupling that exists between P-f and Q-V loops, the quick stabilization of frequency signal also helps to stabilize the terminal voltage.

2.4 The P-Q regulator of the SMES unit:

Though the SMES unit can operate in full four quadrant modes from $+P_{sm}$ to $-P_{sm}$ and $+Q_{sm}$ to $-Q_{sm}$ using GTO converters[4], but due to practical reasons, there is a limit on firing angles which restricts the operating range. They are:

$$|\alpha| = 5°, \text{ in the rectifier mode}$$
$$|\alpha| = 165°, \text{ in the inverter mode}$$

Since the converter operates in continuous mode, the upper limit of the inductor current is set in 1.38 I_{sm0} and the lower limit is $0.31 I_{sm0}$. The ideal no-load maximum direct voltage of the 12- pulse bridges is considered as 2 kV. Taking all these factors into consideration, the limits of the 6 MJ SMES unit can be calculated as [5,7]

$$S_{max} = 9.60 \text{ MVA}$$
$$-9.27 \ge P_{sm} \le 9.50 \text{ MW}$$
$$-9.60 \ge Q_{sm} \le 9.60 \text{ MVAr}$$

2.5 Rule Base for the Fuzzy Controller:

The rule base structures for FFC and FVC are similar, but the values of linguistic variables are different. The general form of the structure is shown in Table 1. While the input variables of the membership function are calculated as described before, the output values are determined as follows:

1. Obtain the value of $\Delta\dot{\omega}$ (k) and $\Delta\dot{V}_t(k)$
2. Compute the maximum and minimum values of the output variable as

For FFC, $PVB = K_{PR} * \Delta\dot{\omega}(k)$ MW & $NVB = -PVB$

If $PVB > 9.5$, then $PVB = 9.5$, and

if $NVB < -9.27$, then $NVB = -9.27$

$PB = 0.75 * PVB$, $NB = -PB$, $PM = 0.5 * PVB$, $NM = -PM$, $PS = 0.25 * PVB$, $NS = -PS$ & $Z = 0$ MW

For FVC, $PVB = K_{VR} * \Delta\dot{V}_t(k)$ MVAr & $NVB = -PVB$

If $PVB > 9.6$, then $PVB = 9.6$, and
if $NVB < -9.6$, then $PVB = -9.6$
$PB = 0.75*PVB$, $NB = -PB$, $PM = 0.5*PVB$,
$NM = -PM$, $PS = 0.25*PVB$, $NS = -PS$ & $Z = 0$ MVAr

The constants K_{PR} and K_{VR} should be chosen in such a way that $K_{PR}*\Delta\dot{\omega}(k) \geq 1$ and also $K_{VR}*\Delta\dot{V}_t(k) \geq 1$. That will allow the SMES unit to provide maximum P-Q modulation.

The rule base for the supplementary signal generation is shown Table 2: The values of all linguistic variables PVB, BP .... NVB are exactly the same as FFC. It is clear that each entry in Table 1 or 2 represents a particular rule. The steps followed to determine the output of the fuzzy controller can be summarized as follows:

1. Obtain one set of input variables for a value of k.
2. Calculate their degree of memberships (μ_i) from their respective membership functions.
3. Evaluate degree of membership for other subsets by the complement relation $\mu_j = 1-\mu_i$
4. Identify the four valid rules in the respective table (stored as look-up table) and calculate the degree of membership μ_{Ri} contributed by each rule R_i [$i = 1,2,3,4$], using MIN operator.
5. Retrieve the amount of output contributed by each rule.
6. Use height defuzzification method to obtain the final crisp value of the output.

3. Computer Simulation

In order to demonstrate the damping effect of the proposed fuzzy controller, computer simulations based on nonlinear differential equations are carried out for small as well as large disturbances. The differential equations are solved in MATLAB environment. All the nonlinearities such as exciter ceiling voltage, SMES voltage limits, inductor current limits have been included.

The performance of the system is shown in Fig. 5, 6 and 7. In these figures, dotted line(.....) represents without supplementary control and solid line (__) represents with supplementary control when SMES unit is present.

Table 1: Rule base structure for FFC and FVC

Error d(error)/dt	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
NVB	NVB	NVB	NVB	NVB	NVB	NB	NM	NS	Z
NB	NVB	NVB	NVB	NVB	NB	NM	NS	Z	PS
NM	NVB	NVB	NVB	NB	NM	NS	Z	PS	PM
NS	NVB	NVB	NB	NM	NS	Z	PS	PM	PB
Z	NVB	NB	NM	NS	Z	PS	PM	PB	PM
PS	NB	NM	NS	Z	PS	PM	PB	PM	PVB
PM	NM	NS	Z	PS	PM	PB	PM	PVB	PVB
PB	NS	Z	PS	PM	PB	PM	PVB	PVB	PVB
PVB	Z	PS	PM	PB	PM	PVB	PVB	PVB	PVB

Table 2: Rule base structure for supplementary signal

P_{sm1} ΔI_{sm}	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
NVB	Z	Z	PS	PS	PM	PB	PVB	PVB	PVB
NB	NS	Z	Z	PS	PS	PM	PB	PVB	PVB
NM	NM	NS	Z	Z	PS	PS	PM	PB	PVB
NS	NM	NS	NS	Z	Z	PS	PM	PB	PVB
Z	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
PS	NVB	NB	NM	NS	Z	Z	PS	PS	PM
PM	NVB	NB	NB	NS	NS	Z	Z	PS	PM
PB	NVB	NVB	NB	NM	NS	NS	Z	Z	PS
PVB	NVB	NVB	NVB	NB	NM	NS	NS	Z	Z

In Fig. 5, the disturbance considered was a sudden increase of 10% in the air gap MVA, followed by a sudden decrease of the same magnitude after the system has settled down. This is considered as a relatively small disturbance.

From the results it is seen that for the case where there is no SMES unit, it takes about 24 seconds for the system to settle down. Compared to this, when the SMES unit is present, all system states settle down in about 2 seconds and the maximum overshoot of $\Delta\omega$ reduces by 76%. The plots of the energy change and power modulation of the 6 MJ SMES unit are also shown in the Fig. 5. In this case, it was found that the addition of supplementary signal does not produce significant changes. This is because the disturbance is small and the system damps very quickly with SMES unit. Figures 6 and 7 show the system responses for a large disturbance in the power system. Two case studies are conducted.

Case 1: A 4-cycle 3-phase fault occurs at the middle of the transmission line.

Case 2: Similar 3-phase fault at the generator bus.

It is seen that without the SMES unit the system exhibits poor damping. Both the angular frequency and terminal voltage oscillate for a very long time.

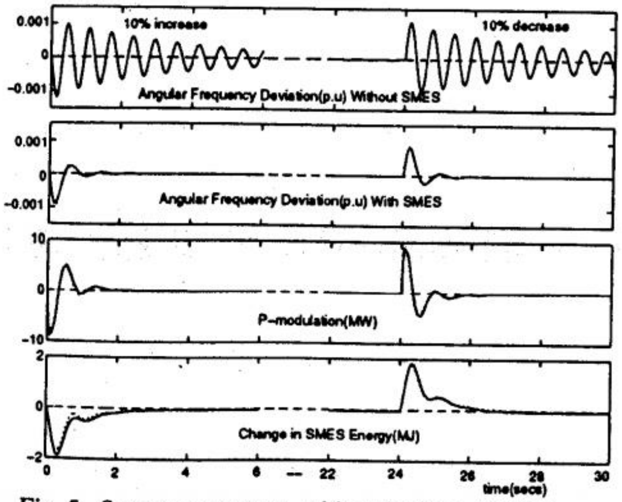

Fig. 5. System responses with and without SMES unit due to small disturbances

After an oscillatory period, the terminal voltage deviation shows a tendency of stabilizing at –0.23 p.u. for case 2 (Fig. 7), when there is no SMES unit. With the addition of SMES unit, both the angular frequency and terminal voltage return to their prefault values very quickly. During the dynamic variation of angular frequency and terminal voltage, P_{sm} and Q_{sm} undergo rapid fluctuation within their respective modulation range. The available Q-modulation is determined by the P-Q regulator after deciding the necessary active power compensation. The effect of on-line generation of the membership functions and the control rules are evident here. It enables the controller to provide appropriate weights to the control rules, and also to the upper and lower bounds of the membership functions of the input variables. Eventually it allows the SMES unit to provide suitable compensation during the oscillatory period. From these results it is concluded that irrespective of the degree of disturbance, the power system returns to the predisturbance position within 3 secs when equipped with the SMES unit. The supplementary control plays an important role to achieve these outputs. Both Figures 6 and 7 show that with supplementary control, the SMES unit is able to provide more compensation after the initial one cycle period. Since the p.u. rating of the SMES unit is rather small compare to the prefault power transfer, for large disturbances, such as these, the SMES can not provide adequate compensation during the first cycle, even though it has reached its upper limit. However after the first one cycle, due this additional compensation the settling time reduces. Increasing the gain of the inductor current deviation was found to reduce the settling time of the change in energy of the SMES unit, but at the expense of an increase in the settling time of the frequency. A brief comparison of the SMES performance with and without SMES unit is given in Table 3.

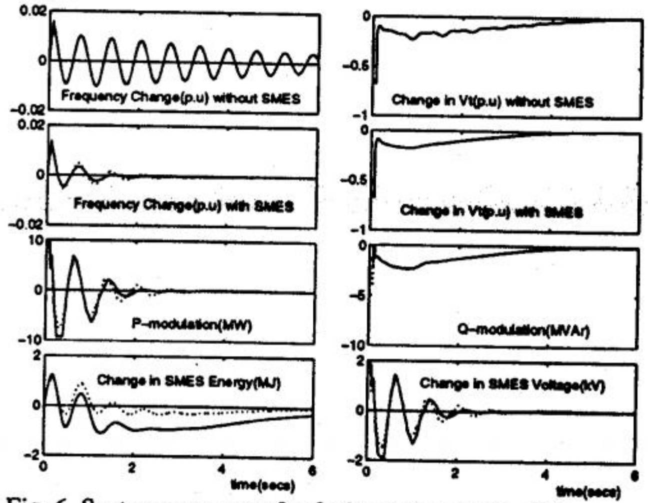

Fig. 6. System responses for fault at the middle of the line

4. Conclusion

In this paper, a simple fuzzy control strategy for the SMES unit is explained. The damping of the synchronous generator is greatly improved by the SMES unit with proposed control system. To ensure the effective use of SMES unit energy, a supplementary control signal is also added to the output of the FFC. The importance of the supplementary control is visualized when the power system is affected by a large disturbance. Since the size of the SMES unit small, therefore in the first cycle the effect of P-Q compensation is not so evident. However, within the next two secs, the SMES unit helps to get excellent damping in power system following any kind of disturbance. On line generations of membership functions makes the controller very sensitive to any kind of disturbance. The scheme proposed in the present paper makes effective use of both active and reactive power modulation of the SMES unit and hence its economic advantage is expected to be stronger than that of earlier schemes. The control strategy is very simple and does not require heavy computation, therefore, implementation is feasible.

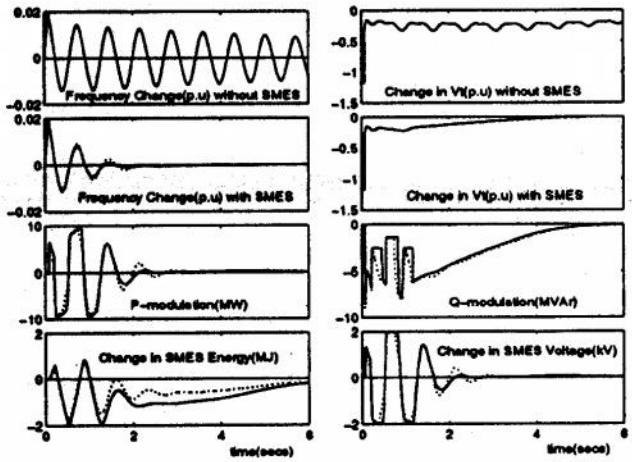

Fig. 7. System response for fault at the generator bus

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Table 3: Comparison of system performance with and without SMES unit

Disturbance Type	Angular Frequency Deviation(p.u.)			Settling Time (secs)	
	Without SMES Peaks 1st / 2nd	With SMES but without supplementary control Peaks 1st / 2nd	With SMES & supplementary control Peaks 1st / 2nd	With SMES but without supplementary control	With SMES & supplementary control
Faultat the middle of the line	.015 / .010	.0133 / .0058	.0133 / .0044	3.55	2.50
Fault at the generator bus	.020 / .013	.0200 / .0118	.0200 / .0110	3.75	2.50

APPENDIX 1

System data and initial conditions[1,5,7]

Generator and transmission line

All parameters are expressed in p.u. unless stated otherwise.

Base 160 MVA, 15 kV

Generator 160 MVA, 15 kV, 0.85 p.f.

Exciter 375 V, 926 A

$X'_d = .245$ $R_a = .001096$ $M_g = 4.74$ $D_g = 0$ $X_d = 1.70$
$X_q = 1.64$ $T'_{q0} = .075$ s $T'_{d0} = 5.9$ s $R_e = .02$ $X_e = 0.4$

Initial power in the air gap: 1.2 + j 0.8129 p.u.
Local load: 0.2 + j 0.2 p.u.

SMES Unit & Fuzzy Model

$I_{sm0} = 4.89897$ kA $V_{sm0} = 0$ kV $L_{sm} = .5$ H $K_W = .05$
$K_i = 3$ $K_{PR} = 60$ $K_{VR} = .02$ $W_{sm0} = 6.0$ MJ