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Analysis of Transient Stability of Superconductor Synchronous Generator at the Presence of Fault Current Superconductor Limiter

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Abstract

One of the most important principles in power networks is system stability. For maximum use of investments in generation, present day systems work at their highest capacity. In other term, they are always at oscillating state and this reduces power system stability drastically. An ordinary generator has some flaws such as small output power density and low efficiency especially upon high powers; however, superconductor generator has higher efficiency than ordinary generator, and similarly, has greater stability upon occurrence of oscillations in power networks. From other side, use of fault current superconductor limiter for rapid removal of fault and ameliorating the transient stability also is effective for generator protection upon fault occurrence. Given above questions, the necessity of study and offering an approach regarding transient stability amelioration, modification of oscillations as well as protecting generators upon fault occurrence seems to be necessary. Here, by modeling an ordinary synchronous generator with infinite bus and comparing it with equal conditions upon fault occurrence with a superconductor generator at the presence of fault current superconductor limiter, we examine the rotor kinetic energy oscillations upon fault occurrence using MATLAB software.

Keywords: superconductor generator, fault current limiter superconductor resistance, transient stability, kinetic energy oscillation.

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1. Introduction

In 1911**,** the Dutch Heike Kamerlingh Onnes from Leiden University upon working in his low temperature laboratory discovered that at temperature 4.2-degree kelvin the electricity current can flow without any potential difference in solid mercury (Power, 1995; Giese & Runde, 1993; Smith et al., 1993; Thuries et al., 1991). He used liquid helium for cooling what has been newly discovered and he called this unique event as superconductivity. He received Nobel physics prize in 1913 for this reason. Superconductivity is a phenomenon that occurs at very low temperature for some materials. In superconductivity, the material electrical resistance becomes exactly zero and the substance would be characterized by full diamagnetic property, that is, magnetic field is the only main difference of superconductors with full conductor, as in full conductor it is expected the magnetic field to be constant, while in superconductor the magnetic field is always zero (Hara et al., 1993; Leung, 2000; Sjostrom et al., 1999; Yagami et al., 2000). The tendency of power system to establish recovery forces equal or greater than the disorder force applied to it, for maintaining system balance is called stability. If the control system fails to cope the disturbance of power system, system becomes unstable and protective devices operate. The stability depends on machine performance upon fault occurrence. System ability in preserving synchronism conditions upon small disturbances is referred to as steady state stability (like transfer of switching from a point in the network to the generator head) and time range for it is a few microseconds. Preservation of power system conditions upon occurrence of large and abrupt disturbances like short circuit of one or three phases or applying abrupt loads to power system is called as transient stability and its time range is few seconds. Superconductor synchronous generators are very promising due to high ability in preserving damping conditions today. From other side, Resistor type superconducting fault current limiters (RSFCL) are effective for rapid removal of fault and improving transient stability and protection of generators upon fault occurrence. Therefore, this study examines the superconducting synchronous generator at the presence of RSFCL and comparing it with ordinary generator. For study we use nonlinear model as well as stability theory in nonlinear systems. For examining transient state, we use single machine system connected to infinite bus. The transient stability analysis is carried out in three veins namely 1.Ordinary synchronous generator, 2.Ordinary synchronous generator with RSFCL and 3. Superconducting

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synchronous generator with RSFCL and the results are discussed (Yagami, 2001; Yagami et al., 1999). This study aims to examine and analyze the use of superconductor generators in ameliorating transient stability and use of RSFCL in power network upon fault occurrence. In 1920, Park innovated a new method for analysis of electrical machines. He used a change of variable in which the variables (Voltages, currents and joint flux) of coils of synchronous machine stator were replaced with corresponding variables related to hypothetical coils located on the rotor (Kirtley, 1993; Alyan & Rahim, 1987). In other words, he transferred the stator variables to fixed reference coordination in the rotor. Park conversion was a great change in analysis of electrical machines, because this change has this unique feature that removes all inductances of time variable from voltage equations of synchronous machine caused by (1) electrical circuit relative movement and (2) electrical circuits with variable magnetic resistance (Minseok, 1986; Superczynski & Waltman, 1997).

2. Research method

Following simulation cases are considered for studying the fault current transient state:

2.1. Simulation of Synchronous generator connected to network with superconducting fault limiter

Upon fault occurrence, the superconductor fault current limiter is also added to model. The modeling procedure for superconductor FCL with SIMULINK is shown in figure 1 (Demiroren & Zeynelgil, 2002).

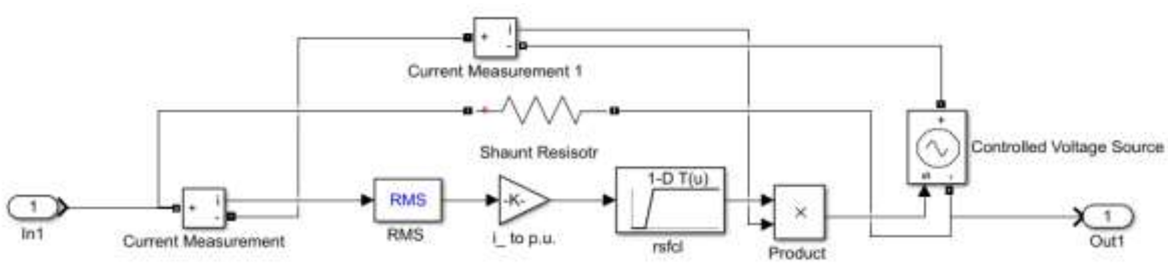

Figure (1). Modeling procedure for superconductor FCL

The principles of work are so that at first the line current is measured, then using effective value of current and table of attributes of superconductor, its resistance value is specified. As both resistance and superconductor current are known, by the product of these two values and a block

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of controlled voltage source, the voltage loss caused by superconducting on the line can be modeled.

2.2 Simulation of synchronous generator connected to network without RSFCL

The relations of dynamic model of superconductor synchronous generator can be obtained in the Laplace form using appropriate function blocks connected together. For simulating and analyzing the machine accurate transient it is necessary to add several new sub models that each denotes the performance of various control functions. These sub models are used in calculation of various values of generator such as steady state, stimulation ring, turbine governor model, power system stabilizer and voltage and current. Superconductor synchronous machine full model which is used for simulation is shown in figure 2 (Demiroren & Zeynelgil, 2002).

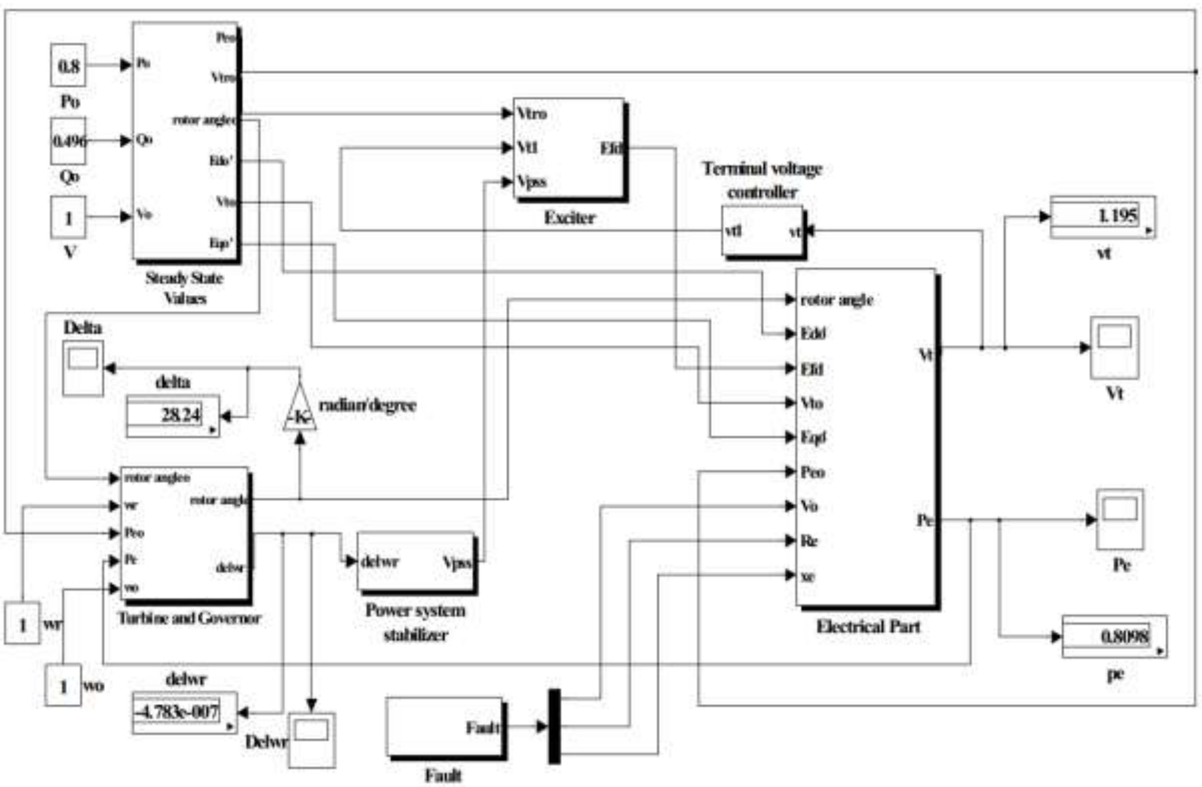

Figure (2). Superconductor synchronous machine full model

2.2.1 Stimulation SIMULINK model

Stimulation circuit is shown by a second order dynamic model in figure 3. The sub model has output E_{fd} and three input V_{tro}, V_t and V_{pss} that denote respectively terminal reference and

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momentary voltage and voltage of power system stabilizer at per-unit value. Efd is output of stimulation system which also includes a feedback.

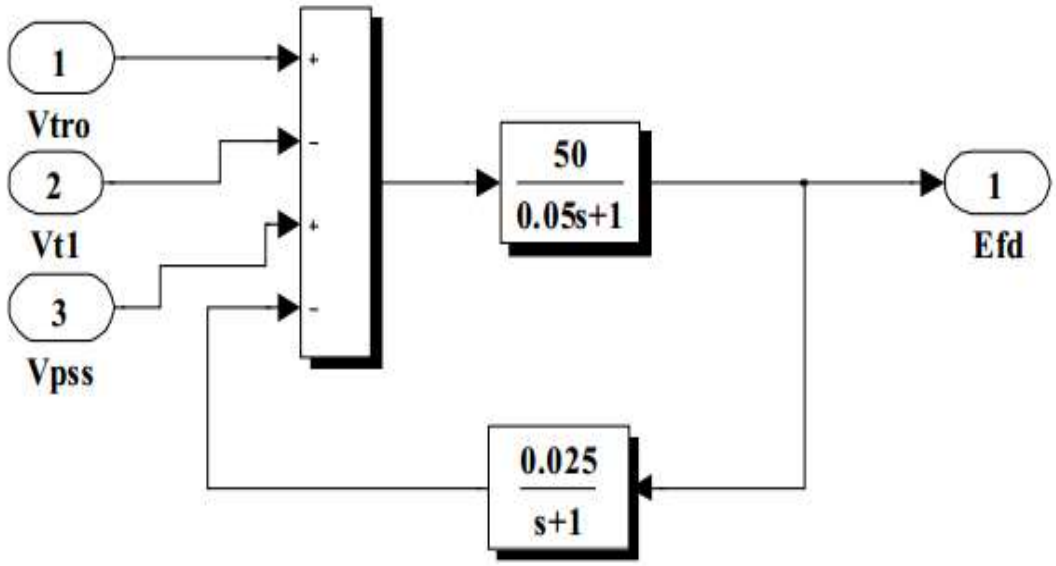

Figure (3). Stimulation system function model

2.2.2. Voltage controller Simulink model

Terminal voltage convertor block is shown in figure (4). This block takes the terminal voltage as input and after rectifying and filtering, compares it with a reference voltage which is desirable terminal voltage.

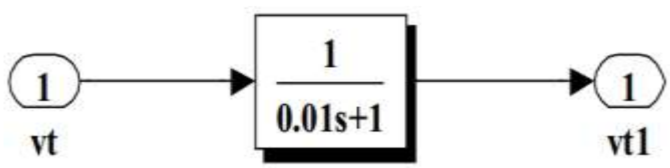

Figure (4). Voltage convertor function model

Here the terminal voltage is calculated as follows:

$$V_{t1} = \frac{1}{1+sT_{SR}} Vt \qquad (1)$$

Where T_{SR} is 0.01.

2.2.3. Electric section SIMULINK model

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The sub model denoted in figure 5 represents the continuous work state of machine electrical parts. Primary values which are used until the time of fault occurrence are provided by two keys in sub model. Sub model inputs include δ , E'_{d0} ،E_{fd} ،V_{t0} ،E'_{q0} ،P_{e0} ،V_0 ،R_e *and* x_e and the outputs include V_t *and* P_e (Demiroren & Zeynelgil, 2002).

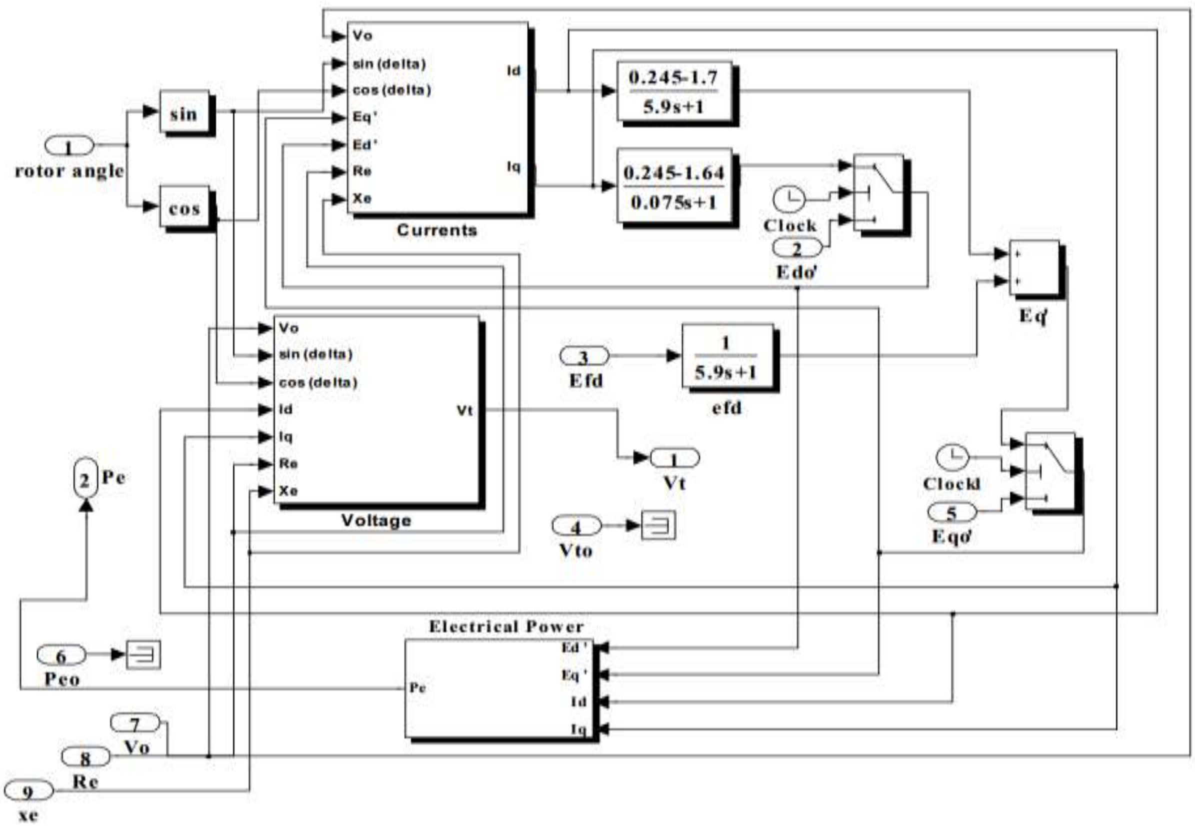

Figure (5). Electric segments continuous work state function model

Values of currents I_d *and* I_q *can be calculated according to relations 2 to 6.*

$$V_{td} = E'_d - R_a I_d - X'_d I_d = -V_0 \sin\delta + R_e I_d + X_e I_q \tag{2}$$

$$V_{tq} = E'_q - R_a I_q + X'_d I_d = V_0 \cos\delta + R_e I_q - X_e I_d \tag{3}$$

$$\begin{bmatrix} E'_d + V_0 \sin\delta \\ E'_q - V_0 \cos\delta \end{bmatrix} = \begin{bmatrix} R_a + R_e & X_e + X'_d \\ -(X_e + X'_d) & R_a + R_e \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \tag{4}$$

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$$E'_d + V_0 \sin\delta = (R_a + R_e) I_d + (X_e + X'_d) I_q \tag{5}$$

$$E'_q - V_0 \cos\delta = -(X_e + X'_d) I_d + (R_a + R_e) I_q \tag{6}$$

By solving above relations, the values of currents of q and d axes are obtained respectively by:

$$I_q = \frac{(X_e + X'_d)(E'_d + V_0 \sin\delta) + (R_a + R_e)(E'_q - V_0 \cos\delta)}{(X_e + X'_d)^2 + (R_a + R_e)^2} \tag{7}$$

$$I_d = \frac{(E'_q - V_0 \cos\delta)}{-(X_e + X'_d)} - (R_a + R_e)\left(\frac{(E'_d + V_0 \sin\delta) + \dfrac{(R_a + R_e)(E'_q - V_0 \cos\delta)}{(X_e + X'_d)}}{(X_e + X'_d)^2 + (R_a + R_e)^2}\right) \tag{8}$$

The value related to terminal voltage can be calculated as follows, given relations 2 and 3.

$$V_{td} = -V_0 \sin\delta + R_e I_d + X_e I_q \tag{9}$$

$$V_{tq} = V_0 \cos\delta + R_e I_q - X_e I_d \tag{10}$$

$$V_t = \sqrt{V_{td}^{\ 2} + V_{tq}^{\ 2}} \tag{11}$$

$$V_t = \sqrt{(-V_0 \sin\delta + R_e I_d + X_e I_q)^2 + (V_{tq} = V_0 \cos\delta + R_e I_q - X_e I_d)^2} \tag{12}$$

Electrical power value namely Pe can be obtained from relation 13.

$$P_e = E'_d I_d + E'_q I_q \tag{13}$$

2.2.4. Simulink model of turbine and governor

Mechanical segment function model is shown by a dynamic model which is depicted in figure 6. The system includes a turbine and governor subsystem as well as blocks which connect the rotor angle δ and angular speed deviations $\Delta\omega$. The sub model includes five inputs, the value of rotor angle in steady state in radian, and the angular speed reference value, permanent and momentary values of electrical power and steady state value of rotor angular speed in per unit. The only output is rotor angle in radian.

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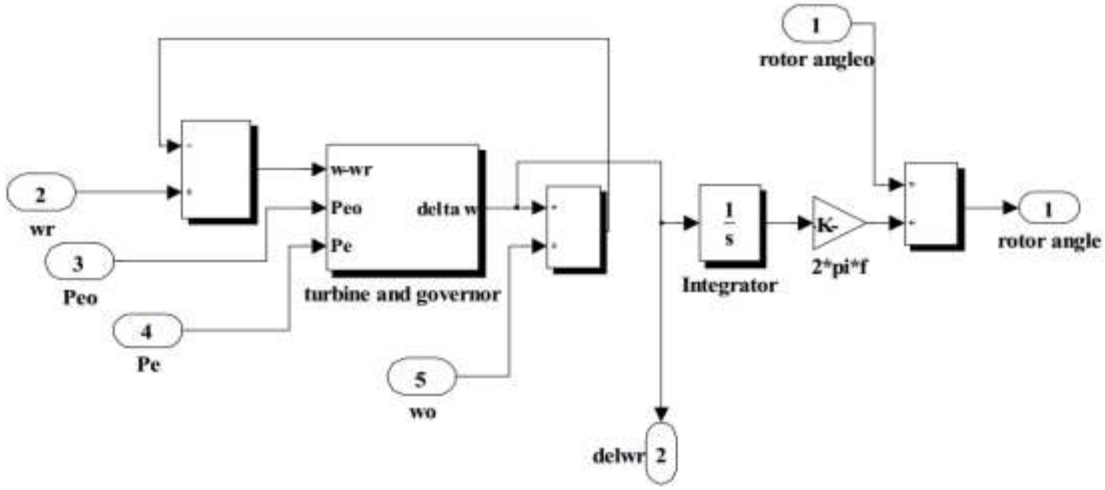

Figure (6). Mechanical segment function model

Turbine and governor system function is shown in figure 7 (Demiroren & Zeynelgil, 2002). This sub model includes three inputs as 1) difference between reference and momentary values of angular speed, 2) the value of steady state of mechanical power and 3) momentary value of electrical power in per unit, and an angular speed difference output in per unit.

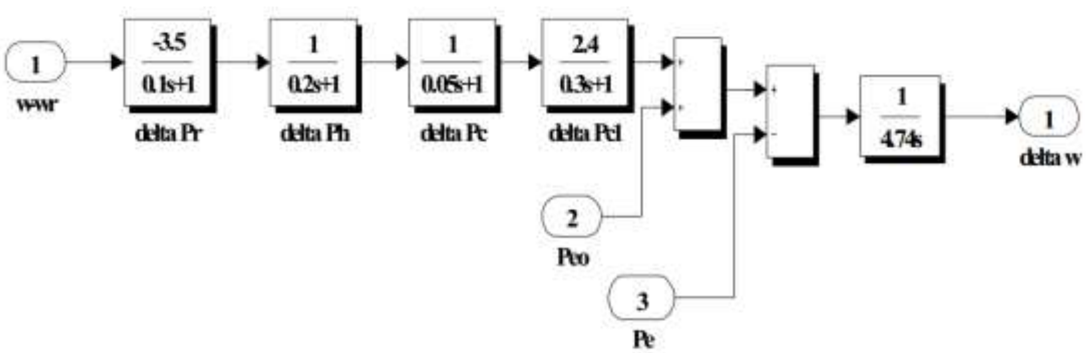

Figure (7). turbine and governor control system

2.2.5. Simulink model of power system stabilizer

Power system stabilizer function model is shown in figure 8 (Demiroren & Zeynelgil, 2002). $\Delta\omega_r$ Which derives from turbine and governor control system is connected to stabilizer gain and phase compensation blocks. The V_{PSS} output is used as input to stimulation system.

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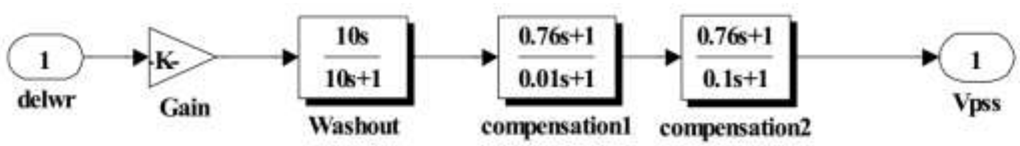

Figure (8). Power system stabilizer model

$$V_{pss} = (K_{STAB}\Delta\omega_r)\frac{sT_\omega}{1+sT_\omega}\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right) \tag{14}$$

2.2.6 Fault Simulink model

For analyzing machine transient state, we have assumed that a three-phase short circuit fault happens at the end of the line and for 0.18 second. The fault is solved in 0.78 second and by swerving the line on which it occurs and then the system goes back to conditions before the fault.

3. Study findings

Superconductor synchronous machine simulation can be done by various simulation tools. MATLAB/SIMULINK and EMTP are among soft wares which are used in various applications. In MATLAB environment, the simulation analysis can be done by programing codes and actuator blocks. For observation of superconductor synchronous machine dynamic behavior, one can use coding of MATLAB environment, however, for analysis of transient state of superconductor synchronous machine, the modeling is conducted in SIMULINK environment and the circuit components of stimulation system, turbine and governor system and power system stabilizer with their details are examined. Among numerical analysis methods, the SIMULINK environment has this ability that show the vectors as block. For this reason, it is more pertinent for didactic applications. SIMULINK model development of circuit components includes calculation of many inputs and outputs of different blocks which together constitute the system. This approach is deemed as a powerful design tool as one can simply observe in it the influence of parameters changes and structure and control methods. Using MATLAB software, modeling, stimulation and analysis can be done in a user graphic interface. SIMULINK includes comprehensive libraries of blocks and various toolboxes for linear and nonlinear analysis. The results of conducted simulations will be discussed in the following sections.

3.1 Synchronous generator simulation in single machine system connected to infinite bus, without fault current limiter

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A part of block diagram prepared for simulation in SIMULINK environment is depicted in figure 9. This part includes synchronous machine with governor and stimulation system which is connected as a single machine system to the infinite Bus.

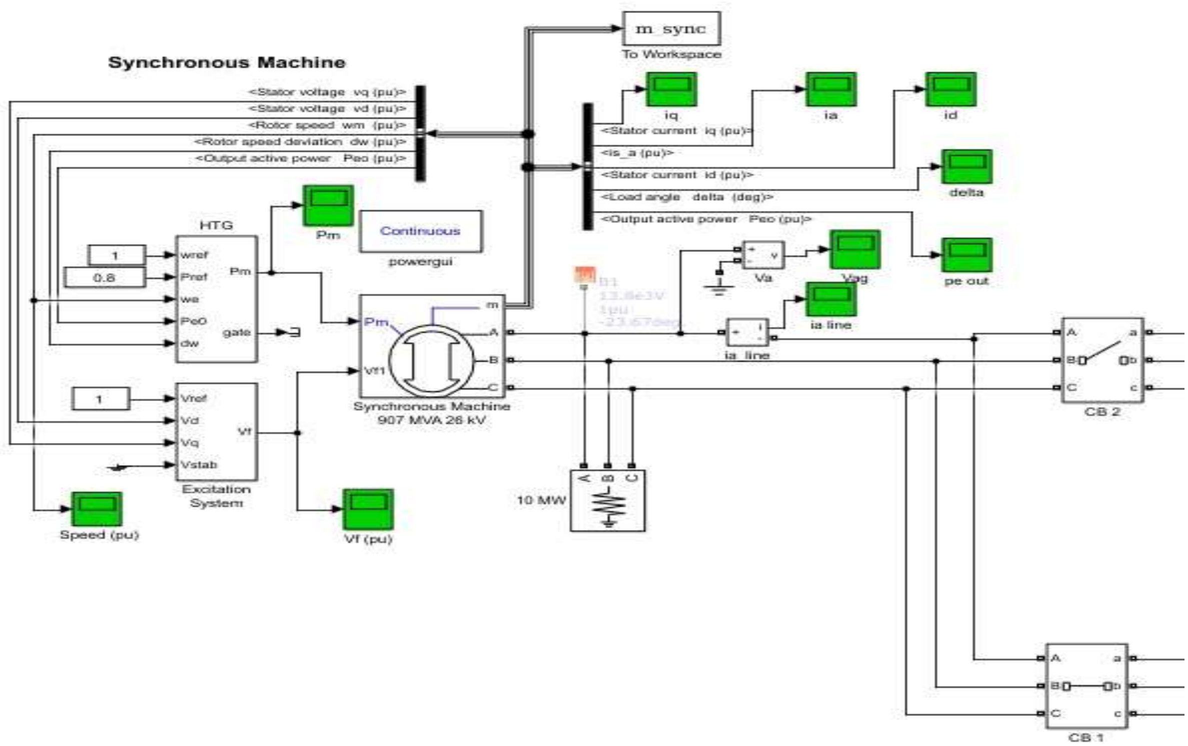

Figure (9). Synchronous machine with governor and stimulation system

We have assumed that the fault is occurred at the end of line. The modeling of three phase fault is done by three phase fault block which can be seen in figure 10.

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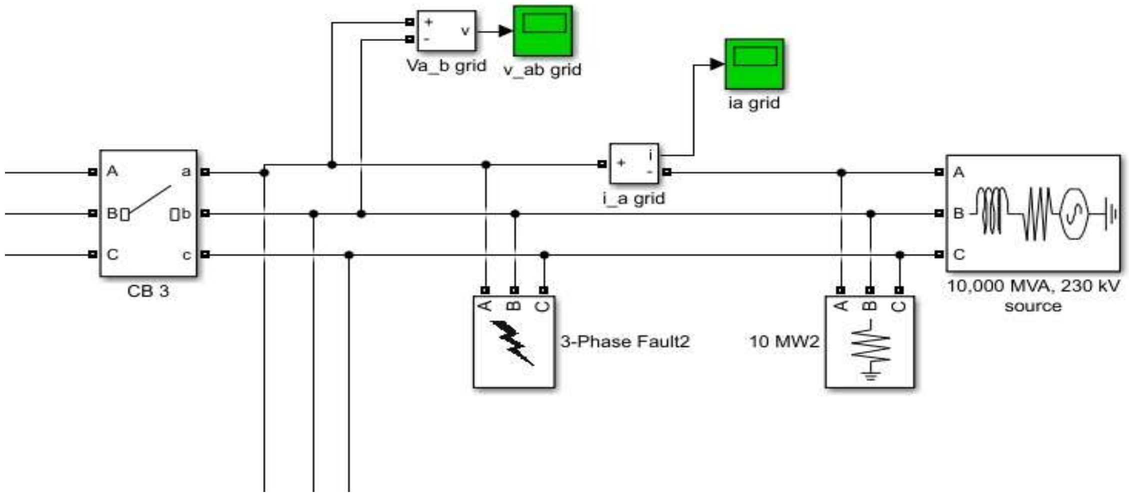

Figure (10). Infinite bus blocks and three phase fault

In this stimulation mode, the fault current limiter is separated from the line by circuit breakers and single machine system is without fault current limiter. By assuming a three phase fault to ground, the obtained wave's forms are indicated in figures 11, 12 and 13. The load angle of synchronous generator is per degree and the results show that before occurrence of fault, its value was 59 degrees and the system was almost at stable state. At the instant of fault occurrence, its value starts to oscillate and after resolving the fault, and after some oscillations, it levels off to stable value of 62 degrees. Calculated currents of d and q axes of synchronous generator show that the range of current disturbance I_d caused by fault occurrence increases up to 8 per unit. Steady state value of this current is almost 0.95 per unit. The range of disturbances of current I_q caused by occurrence of fault increases up to 6 per unit. Steady state value of this current is almost 0.32 per unit. According to obtained results on the stator phase current (I_{sa}), the amplitude of fault current at the instant of fault occurrence increases up to 9 times, similarly, the changes of rotor speed also increases up to 1.7 % after fault occurrence. The machine output power at the time before fault occurrence till after reaching to stability state shows that during the fault incurrence machine output power is roughly zero. This is due to the zero-machine output voltage upon occurrence of three phase fault. Similarly, changes in phase A machine voltage (V_a) show that the machine voltage amplitude upon fault occurrence decreases roughly 400 times. According to simulation

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results, line current in phase A (i_{line_a}) becomes nearly 10 times after fault occurrence. The three phase current and voltage wave forms upon fault occurrence are depicted in Figure 11 and Figure 12 respectively.

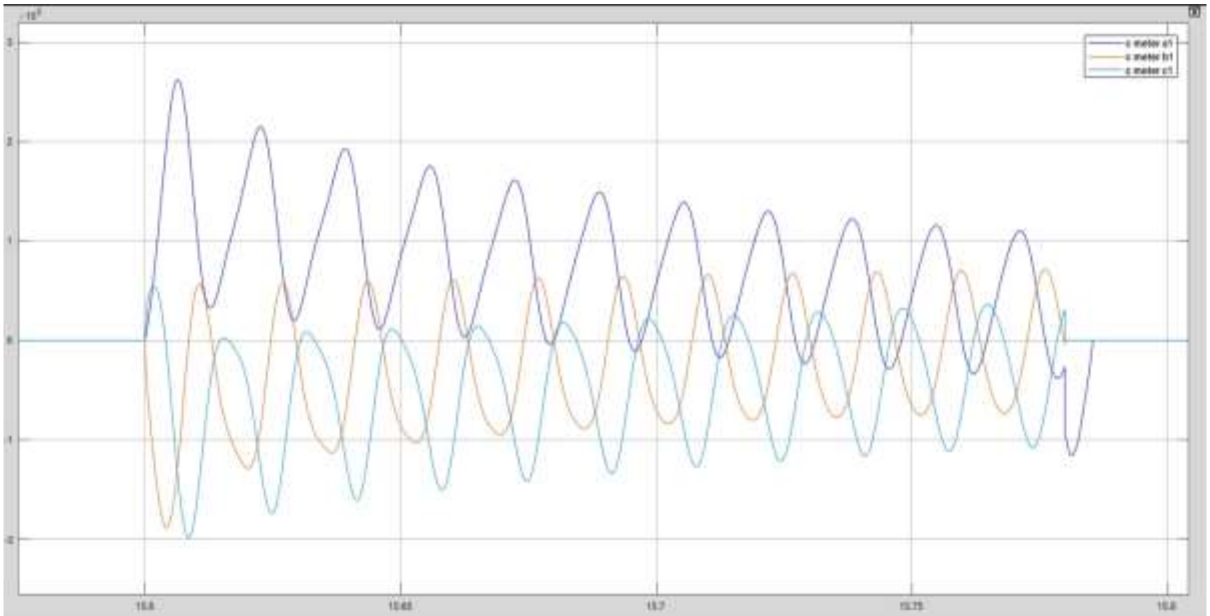

Figure (11). Three phase fault current

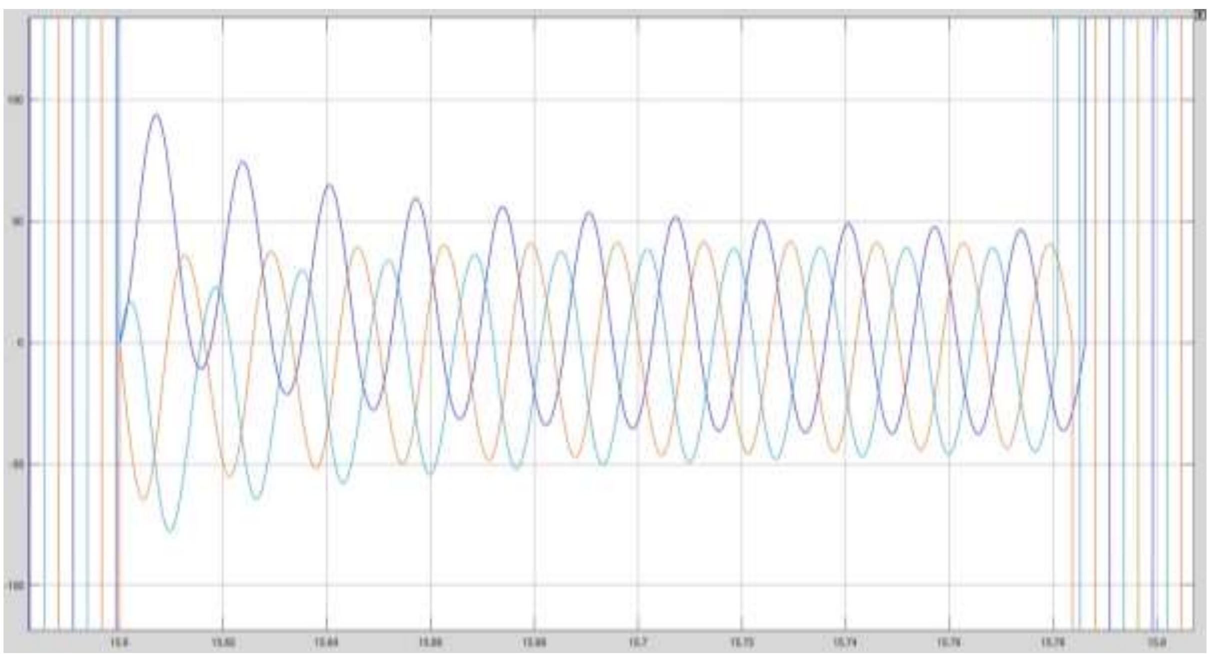

Figure (12). Three phase fault voltage

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Fault current for infinite bus side is also depicted in figure 13.

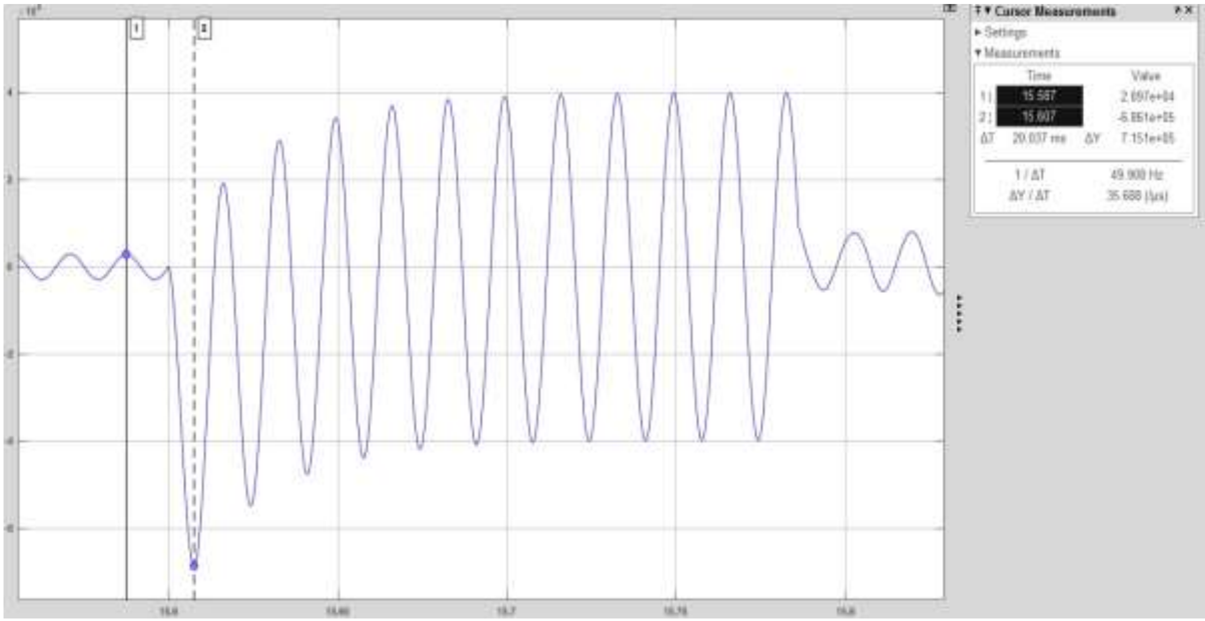

Figure (13). Infinite bus side fault current

3.2 Synchronous generator simulation in single machine system connected to infinite bus by fault current limiter

Modeling for fault current superconductor limiter is as figure (14). In this case, by using circuit breakers, the limiter enters the circuit upon fault occurrence, however, the fault current limiter includes a parallel resistance value.

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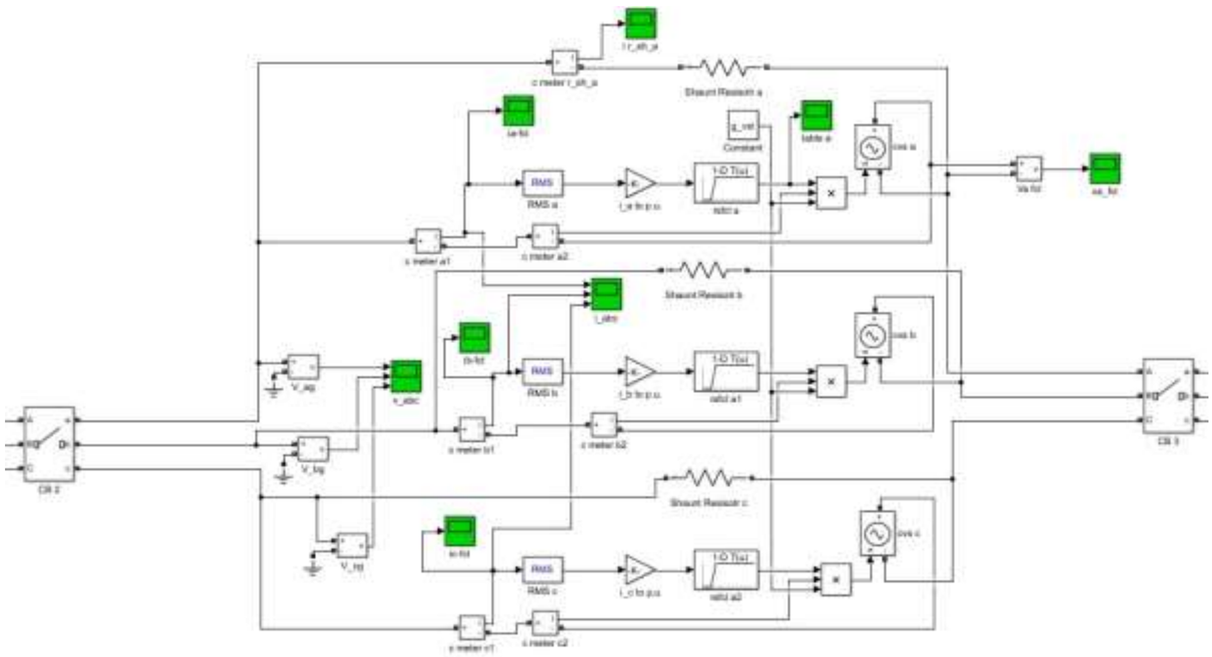

Figure (14). Fault current superconductor limiter modeling

The synchronous generator load angle per degree shows that before fault occurrence, its value is 59 degrees the system is almost in stable state. Upon fault occurrence, its value starts to oscillate and after removal of fault and after some oscillations it levels off at stable value of 64 degrees. The results for d and q currents of synchronous generator show that the amplitude of current disturbances of I_d caused by fault occurrence increases up to 4.5 times. The steady state value of this current is nearly 0.95 per unit. The current disturbance amplitude I_q caused by fault occurrence increases up to 1 per unit. The steady state value of this current is 0.32 per unit. The results of phase a stator current (I_{Sa}) denote that the fault current amplitude upon fault occurrence increases up to 4 times. Similarly, the results of rotor speed changes show that rotor speed after fault occurrence decreases by nearly 3.5 %. The results of machine output power before fault occurrence till reaching to stable state indicates that during fault occurrence, the machine output power not only is not zero, but also increases. The reason for that is increase in machine output current and small changes in output voltage upon three phase fault occurrence. The influence of fault current limiter is fully obvious in this result. According to results of phase a voltage changes, the amplitude of voltage of machine upon occurrence of fault nearly does not drop. The results from phase a line

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current i_{line_a}show that current amplitude after fault occurrence is roughly 3 times. Three phase current and voltage wave forms upon fault occurrence are indicated in figures (15) and (16) respectively.

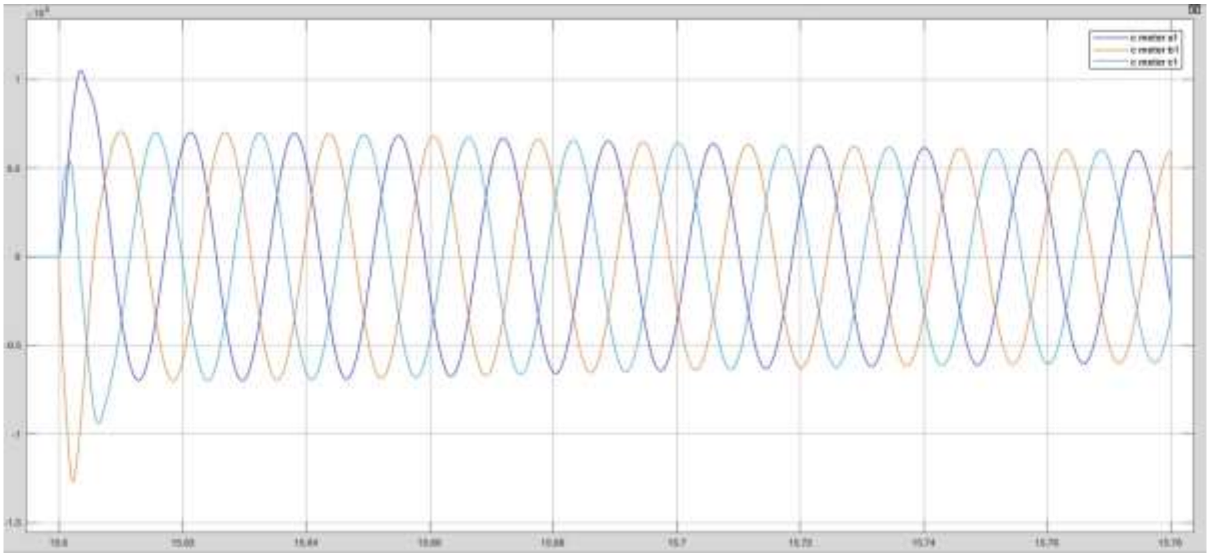

Figure (15). Three phase fault current

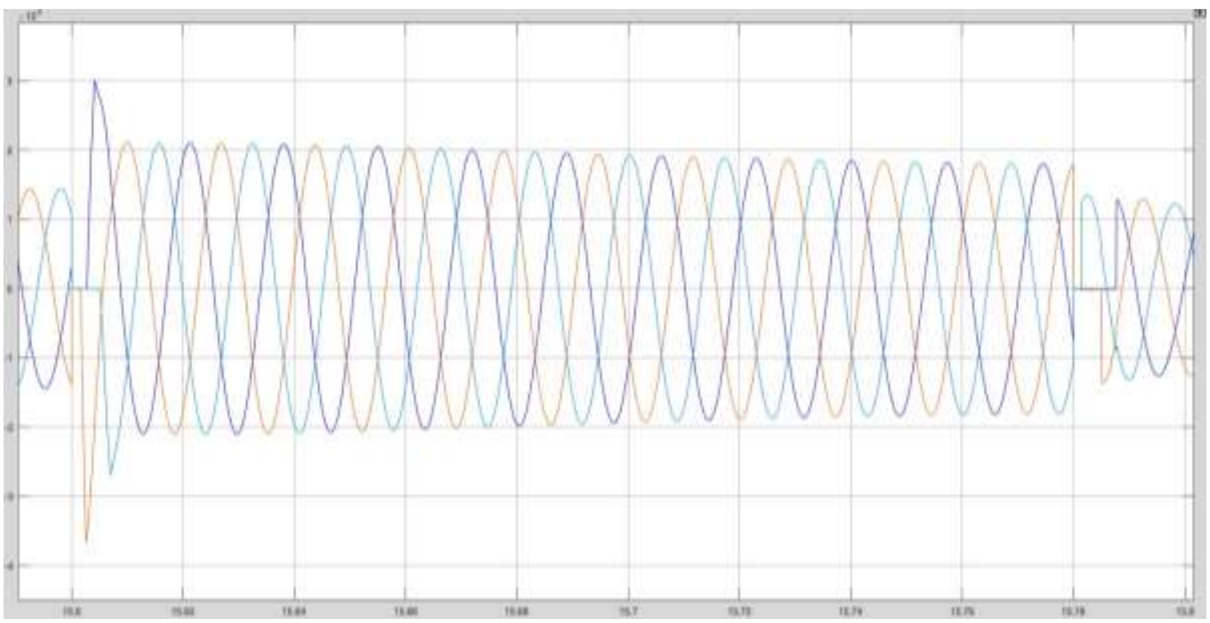

Figure (16). Three phase voltage upon the fault occurrence.

Infinite bus fault current is shown in figure (17).

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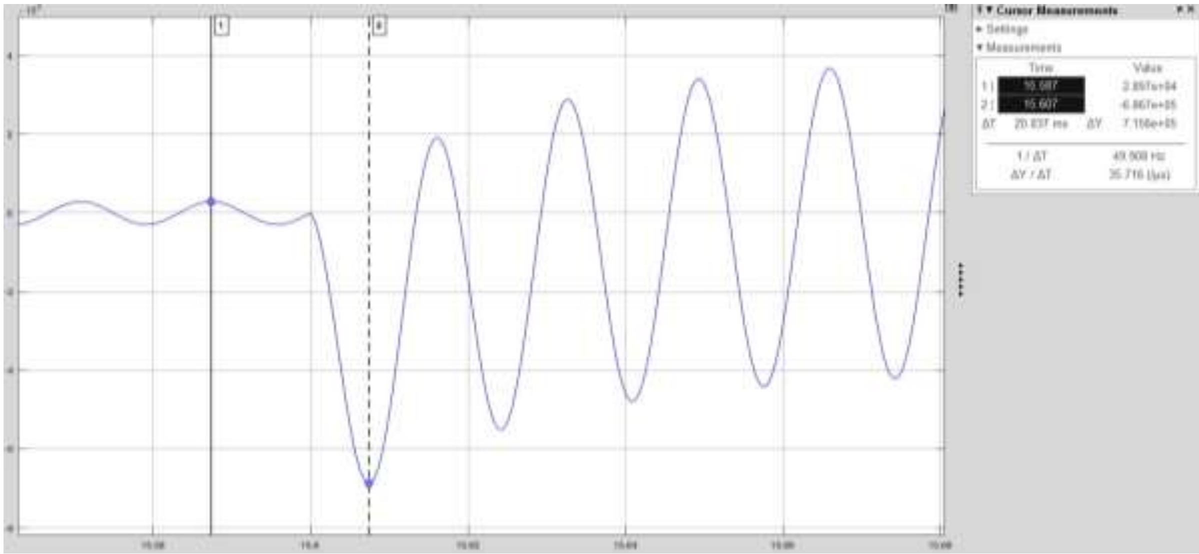

Figure (17) infinite bus fault current

Fault limiter current and voltage wave forms are shown in figures (18) and (19). According to these figures, fault current limiter has no effect in normal operation of circuit and its voltage and current are zero. However, after fault occurrence, by drastic increase of its resistance value, it severely decreases fault voltage and as we saw it causes synchronous machine output voltage level does not drop significantly.

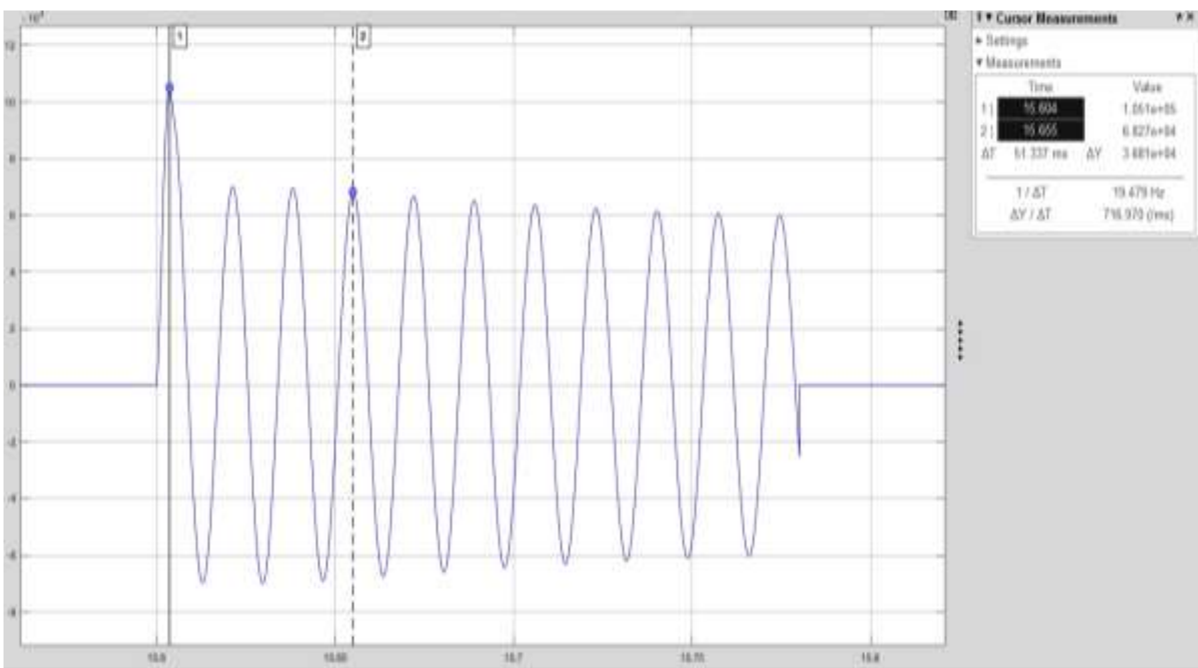

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Figure (18). Fault limiter current wave form.

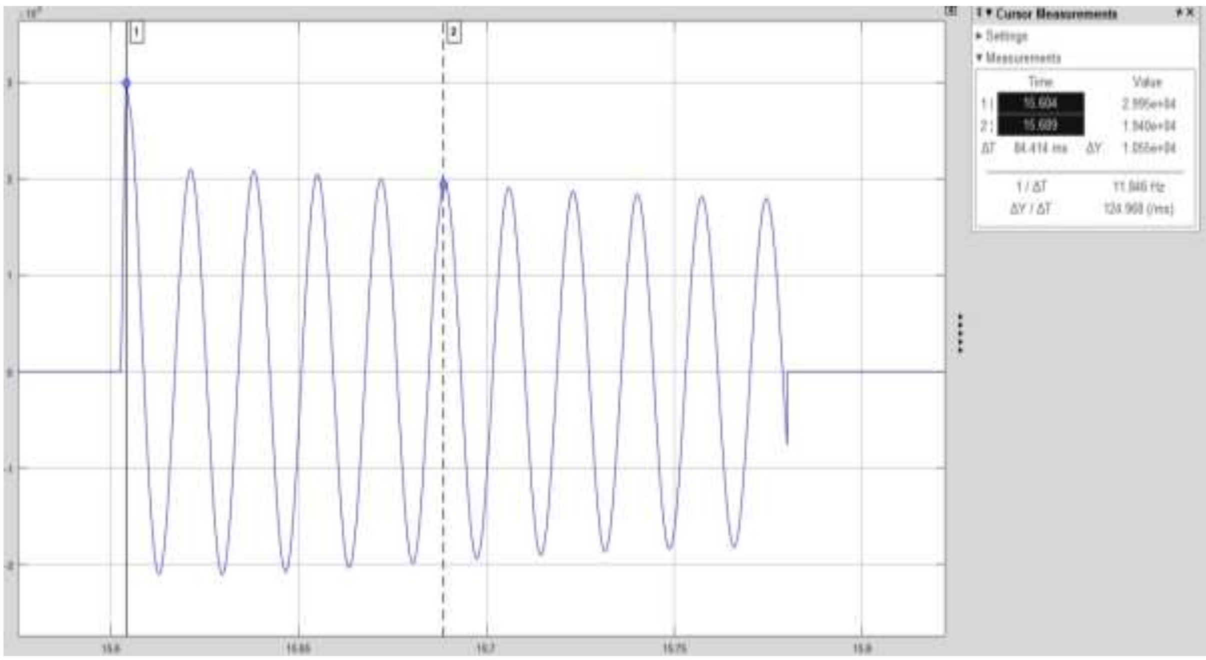

Figure (19). Fault limiter voltage wave form

The phase a current wave form of fault limiter parallel resistance is also shown in figure (20).

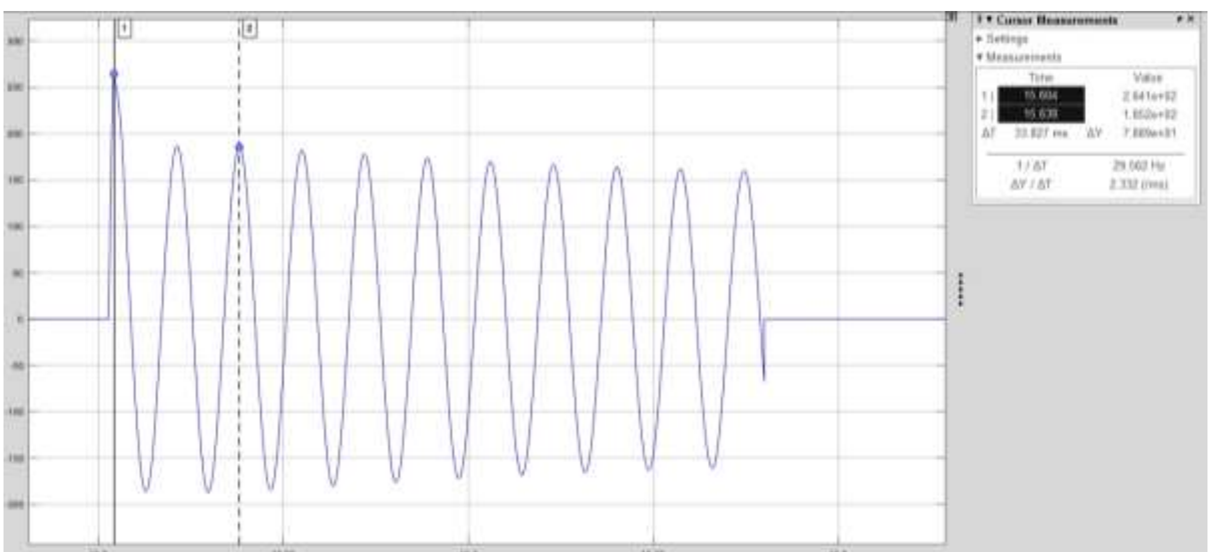

Figure (20). the phase a current wave form of fault limiter parallel resistance

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3.3. Simulation of superconductor synchronous generator in single machine system connected to infinite bus, by fault current limiter

The final model obtained for superconductor synchronous generator in Simulink is indicated in figure (21). At the beginning, for generator the no load fault simulation has seen carried out. After examining the no load fault results, the load fault simulation results with fault current limiter are also presented.

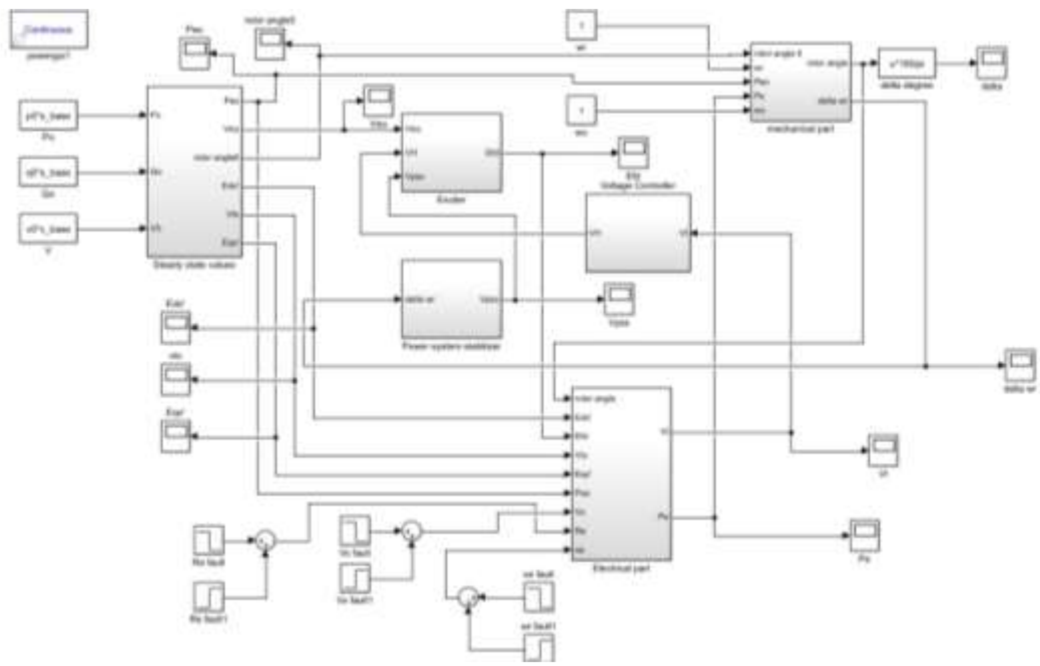

Figure (21). Superconductor generator model

We have assumed that the fault occurs at generator stable work state. The changes of output power and output voltage with respect to steady state results are nearly 1.4 per unit for voltage and 0.8 per unit for power. In this case, d and q axes currents are as figures (22) and (23). The Value of i_d in steady state is nearly -0.8 per unit and the value of i_q in steady state is nearly 0.56 per unit.

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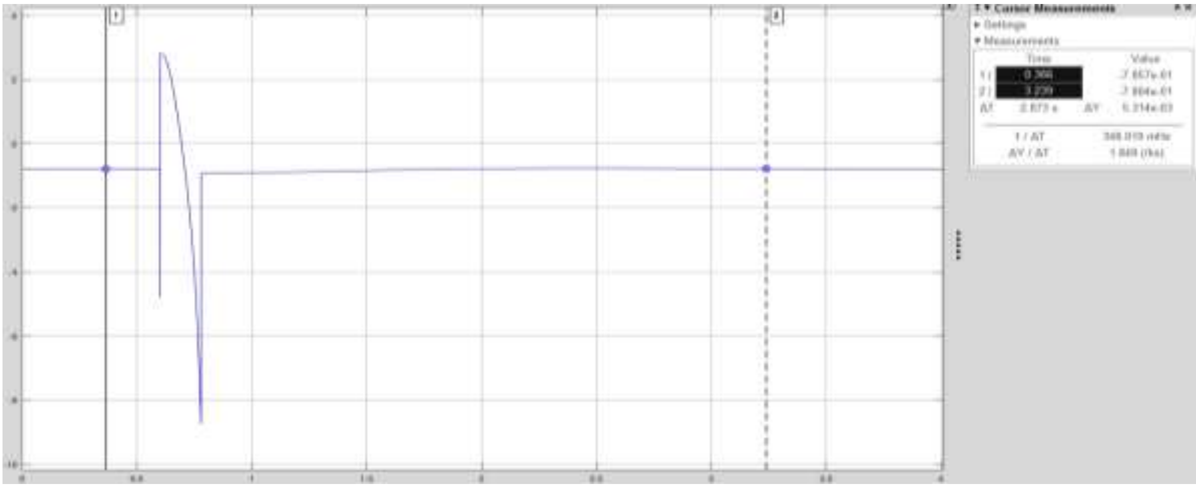

Figure (22). d axis current of superconductor generator

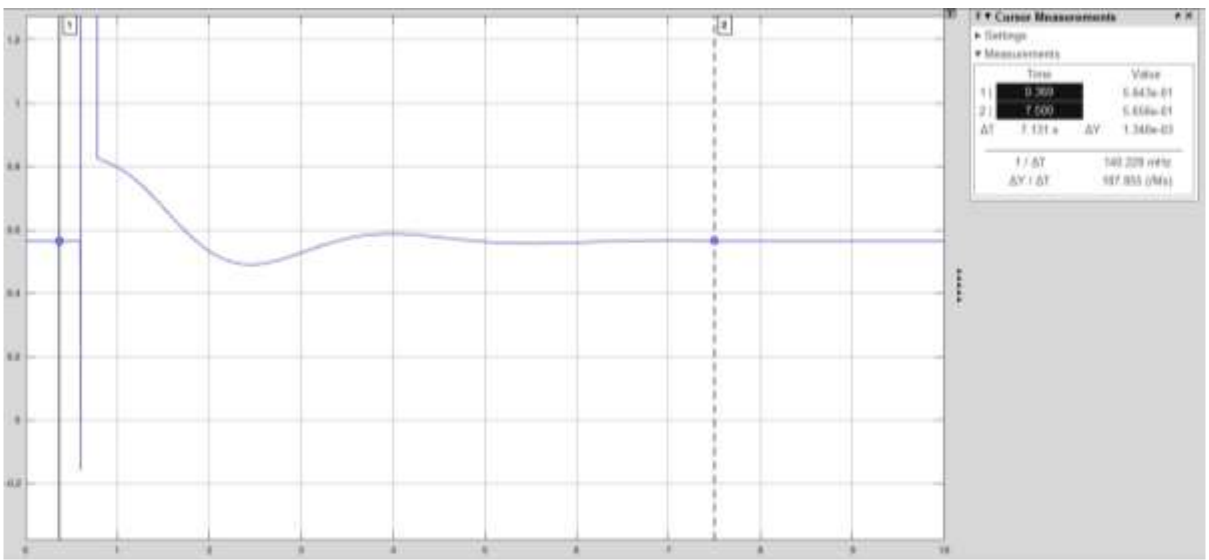

Figure (23). q axis current of superconductor generator

The results of angular speed and rotor angle also show that angular speed due to fault changes is nearly 15%, and it levels off again to its stable state. The rotor load angle in steady state is nearly 21 degrees and due to fault it changes nearly 50%. The oscillations caused by fault are damped by power stabilizer. The generator power stabilizer output voltage in this case is shown in figure (24).

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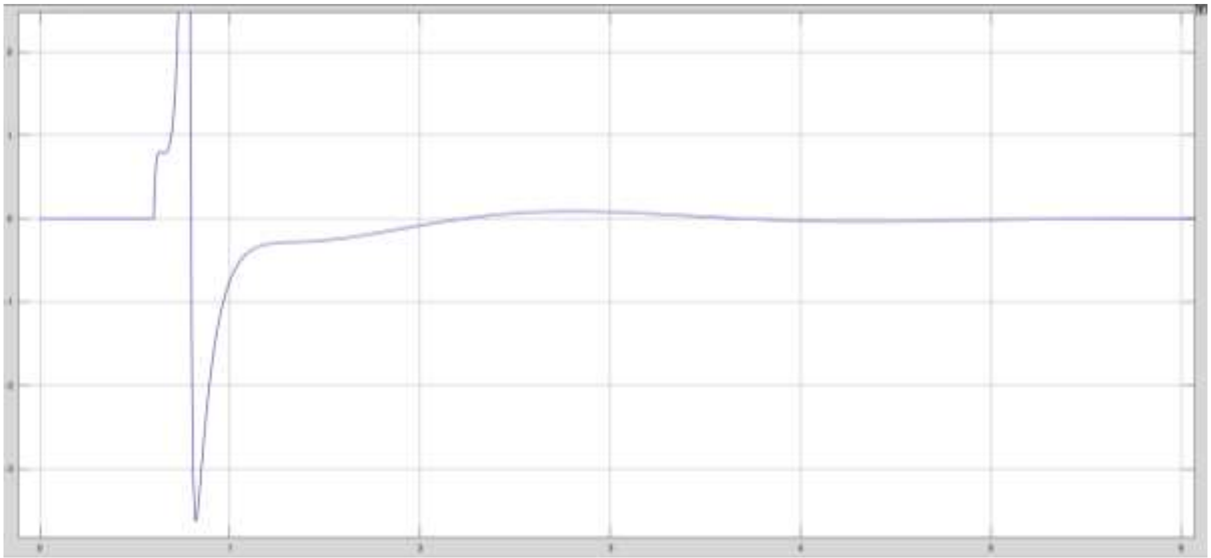

Figure (24). Output voltage of power stabilizer

The results of modeling for superconductor synchronous generator in single machine network connected to infinite bus with fault current superconductor limiter are presented in this section. Synchronous generator load angle in degrees shows that before fault occurrence, the system is nearly at stable state and its value is 14 degrees. Upon fault occurrence, its value starts to oscillate and after removal of fault and after some oscillations it levels off at 13 degrees. Similarly, the results of d and q axes currents of synchronous generator show that the current disturbance amplitude i_d caused by fault occurrence increases up to nearly 2 per unit. The value of permanent state of this current is nearly 0.3 per unit. The current disturbance amplitude i_q caused by fault occurrence increases up to 4 times. The steady state value of this current is nearly 0.77 per unit.

According to the results of phase a stator current i_{s_a}, the amplitude of fault current during fault occurrence increases up to 4 times. Similarly, according to changes of rotor speed, rotor speed after fault occurrence decreases nearly 4%. According to simulation results machine output power before fault occurrence till after leveling off at stability state, in time interval of fault occurrence, not only fails to become zero but also increases. The reason for that is increase of machine output current and very slight change in machine output voltage upon three phase fault occurrence. The effect of fault current limiter is fully obvious in this result. Similarly, according to changes of phase a machine voltage (V_a), the amplitude of machine voltage upon fault occurrence almost doesn't

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decrease. According to phase a line current (i_{line_a}) the current amplitude after fault occurrence becomes almost 4 times. The three phase current and voltage wave forms upon fault occurrence are displayed in figures (25) and (26) respectively.

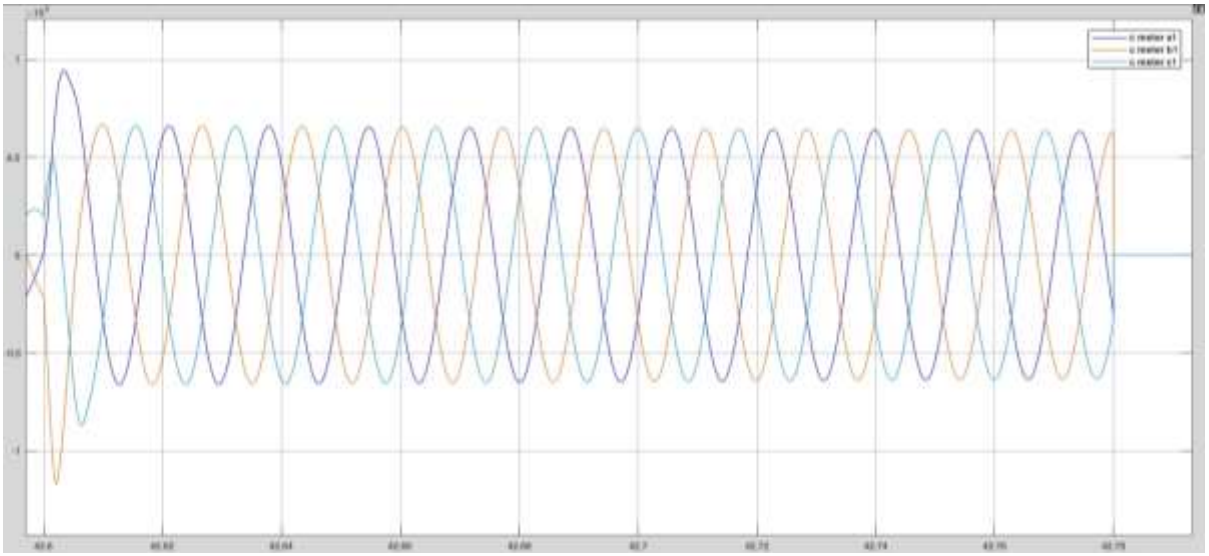

Figure (25). Three phase fault current of superconductor synchronous generator

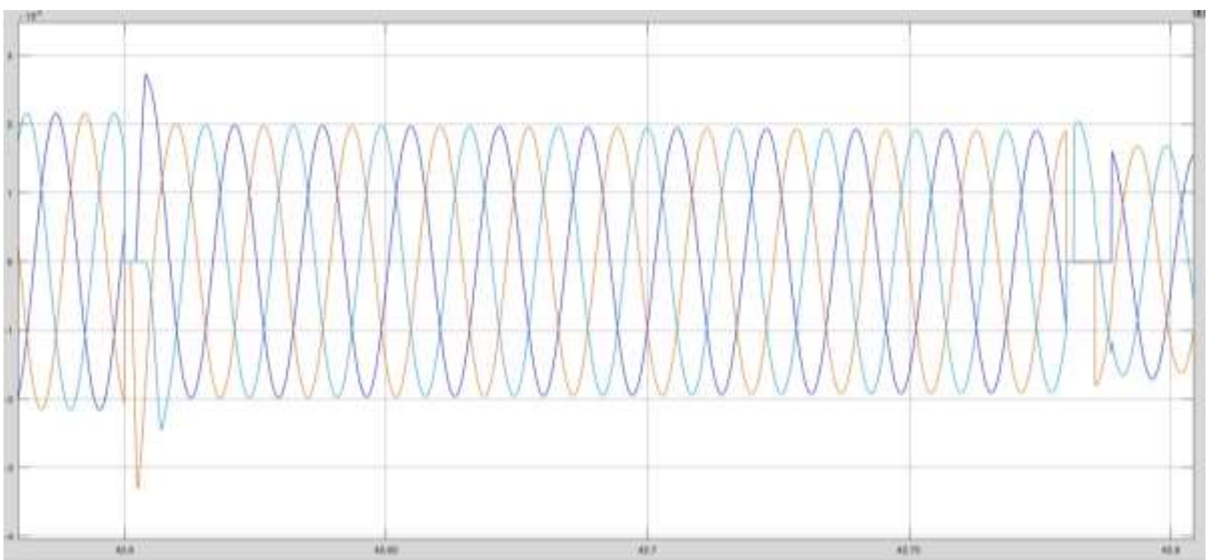

Figure (26). Three phase fault voltage of superconductor synchronous generator

The wave form of fault current of infinite bus is shown in figure 27.

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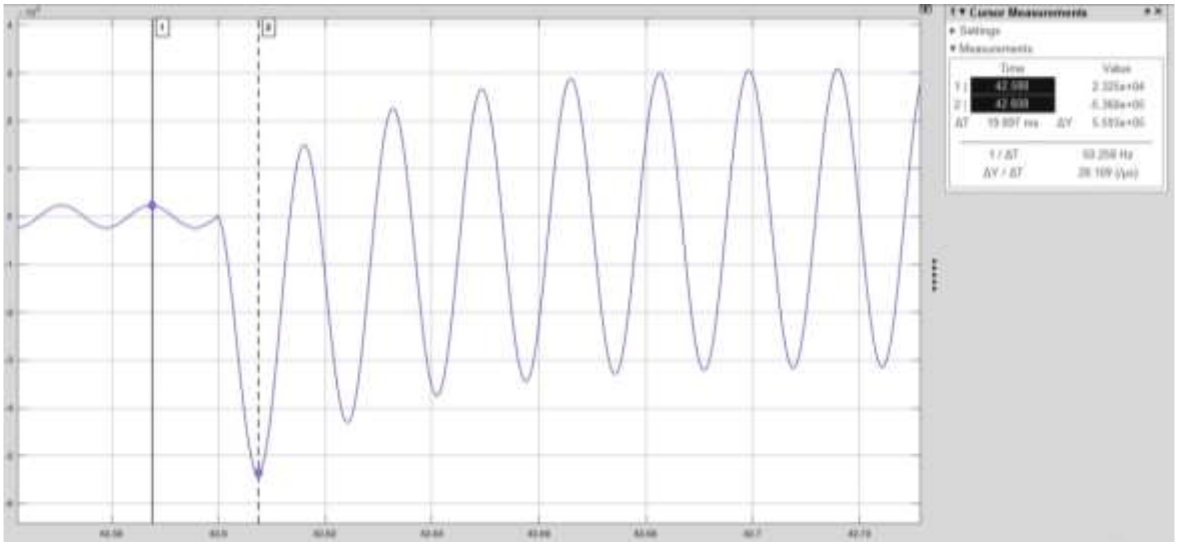

Figure (27). Infinite bus fault current

The wave forms of fault limiter current and voltage are shown in figures 28 and 29 respectively. According to these figures, the fault current limiter has no effect in circuit normal operation and its voltage and current are zero, however, after fault occurrence, by drastic increase of its resistive value, the fault voltage decreases severely and as we saw it causes the output voltage level of synchronous machine doesn't decrease much.

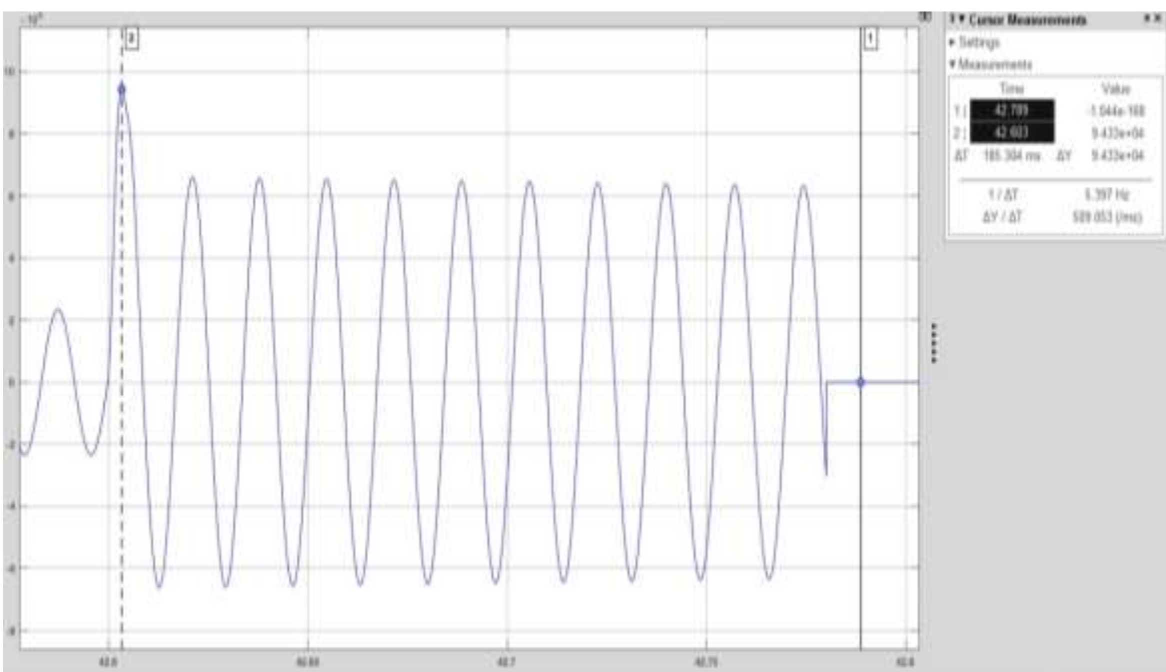

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Figure (28). Current wave form of fault limiter

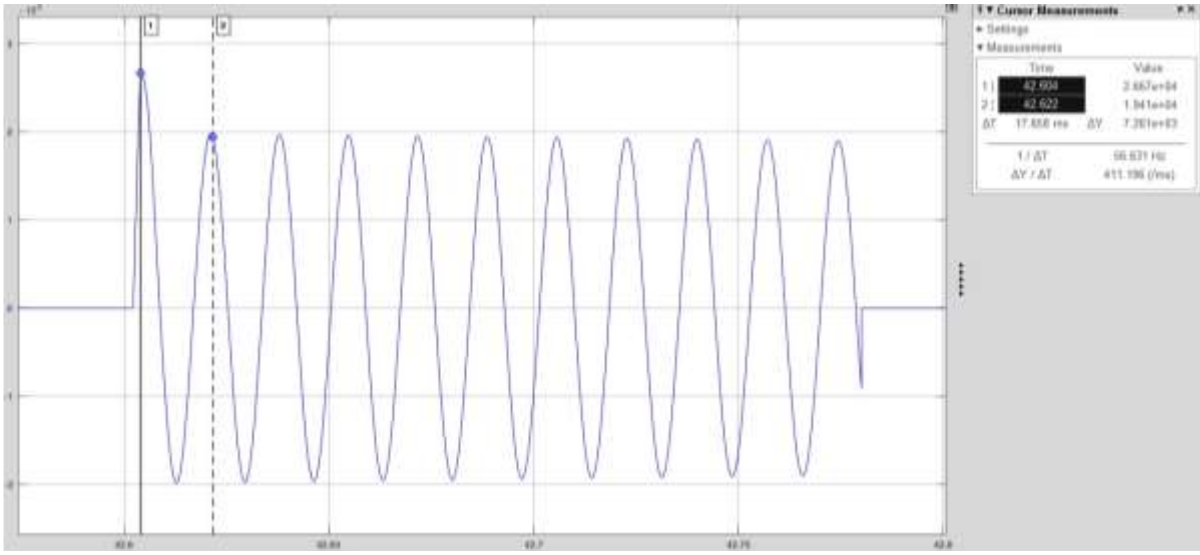

Figure (29). Voltage wave form of fault limiter

At the end, the value of phase a current of fault current limiter parallel resistance is shown in fig (30).

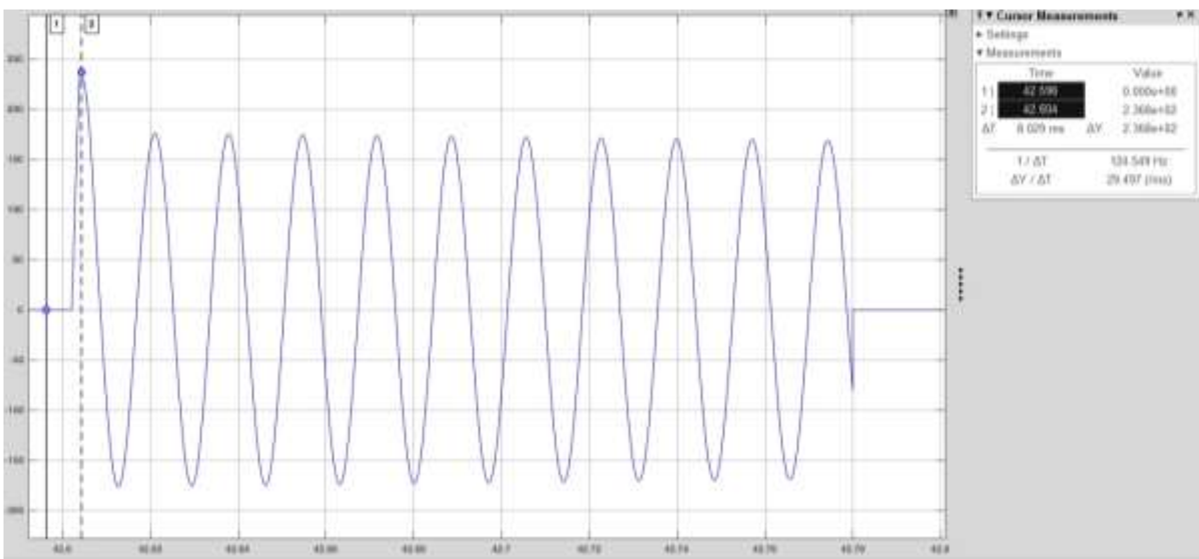

Figure (30). Phase a current of fault limiter parallel resistance

4. Conclusion

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According to simulation results, the effect of presence of superconductor fault current limiter upon fault occurrence can be summarized as:

- Fault current limiter causes line fault current decreases about 30% of its maximum value.
- Fault current limiter causes the stator fault current decreases about 40% of its maximum value.
- Fault current limiter causes stator d axis current decreases to nearly 55% of its maximum value.
- Fault current limiter causes stator q axis current decreases to nearly 16% of its maximum value.

These results are true for superconductor generator at the presence of fault current limiter. By comparing superconductor and ordinary generator performances one can note that due to larger time constant of superconductor generator damping time of its oscillations is more than dampening time for oscillations of ordinary generator. However, due to inherent property of superconductor coil, the amplitude of fluctuations in stator current is less than that of ordinary generator. For example, in simulations we noticed that the d axis current of ordinary generator increases up to 4.5 per unit, but in superconductor generator, fault current of d axis is limited to 2 per unit. One can assume superconductor synchronous generator has internal current limiter due to its coil superconductor properties.

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