Improvement of Power System Transient Stability Using a Controllable Resistor Type Fault Current Limiter

M. Tarafdar Hagh, S. B. Naderi, M. Jafari

***Abstract*—In this paper a variable and controllable resistor type fault current limiter (FCL) is introduced for enhancement of transient stability of single machine infinite bus (SMIB) system with a double circuit transmission line. The optimal value of resistor during fault to reach the maximum stability of power system is computed. It is shown that, this optimal value depends on the fault location and the pre-fault active power of synchronous generator considering power demand changing. To show the effectiveness of the proposed FCL, analytical analysis including transient stability study and optimum resistor value calculation are presented. In addition, simulation results using PSCAD/EMTDC software are included to confirm the analytical analysis accuracy.**

***Keywords*: fault current limiter, optimum resistor, transient stability, synchronous generator, self turn off switch, duty cycle.**

I. Introduction

POWER systems have become more expanded and complicated because of the growth of electric power demand. To reach the more reliability for power supply and overcome increasing power demand, the electric power systems are interconnected each other and the power generation systems are incremented. So, the available fault current levels may exceed the maximum short circuit rating of power system equipments. Under these conditions, limiting the fault currents is an important subject [1-3].

Traditionally, to moderate the cost of switchgear and bus replacements, the most common ways to limit high-level fault currents are: splitting the power grid and introducing higher voltage connections, using current-limiting fuses or series reactors or high-impedance transformers, and using complex strategies like sequential network tripping. A better idea to limit the fault currents and prevent high costs is usage of Fault current limiters (FCLs) [4-5].

Different topologies of FCLs are introduced in literature, such as solid state and superconducting FCLs [6-9]. One group of these structures is R-type superconducting FCLs (RSFCLs). RSFCLs limit the fault current by using resistance and consume the excessive energy of the faults [10-13]. However, superconducting FCLs (SFCLs) have two main problems. Firstly, because of high construction and maintenance cost of superconductors, these devices are not commercially available. Secondly, resistance of RSFCL is not constant during the fault due to its quenching characteristics [13]. So, they are not fully controllable.

The resistor type FCL which is capable of consuming the active power can be applied to the enhancement of power system transient stability by absorbing the accelerating power of generator during fault. On the other hand, determination of optimum value of R-type FCLs resistance is important from transient stability point of view [10, 13- 14]. So a controllable resistor is necessary to insert the optimal value of resistance to the utility to achieve the best improvement of transient stability.

This paper presented a variable and controllable resistor type fault current limiter to improve the transient stability of power systems in addition to fault current limitation. The proposed FCL is capable to control the value of resistor that enters current path, during fault. This value depends on the fault location and the pre-fault active power variation of synchronous generator considering power demand. The analytical analysis to compute the optimal value of resistor which leads to maximum stability of power system is presented in detail. The simulation study using PSCAD/EMTDC software including the proposed FCL is established.

II. Power Circuit Topology and Principles of Operation of the Proposed FCL

A. Power Circuit Topology

The Three phase power circuit topology of the proposed FCL is shown in Fig. 1. This structure is composed of three main parts that are described as follows:

1) The three phase transformer in series with the system that is named "*isolation transformer*".
2) The three phase diode rectifier bridge.
3) A self turn off semiconductor switch (such as GTO, IGBT, etc) in parallel with a large resistor (R). This part is the most important part of the proposed FCL that plays main current limiting role.

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Mehrdad Tarafdar Hagh is with Faculty of Electrical Engineering, University of Tabriz, TU 51666-1647 IRAN (e-mail of corresponding author: tarafdar@tabrizu.ac.ir).
Seyed Behzad Naderi is with Faculty of Electrical Engineering, University of Tabriz, TU 51666-1647 IRAN (e-mail: s.b.naderi87@ms.tabrizu.ac.ir).
Mehdi Jafari is with Faculty of Electrical Engineering, University of Tabriz, TU 51666-1647 IRAN (e-mail: m.jafari87@ms.tabrizu.ac.ir).

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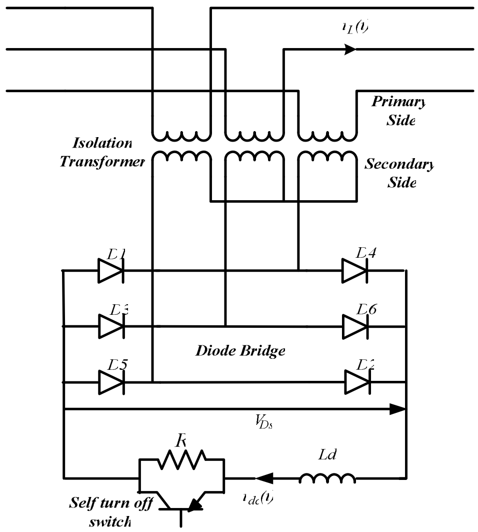

Fig. 1. The three phase power circuit topology of the proposed FCL

A small dc reactor (L_d) is placed in series with the self turn off switch to protect it against severe di/dt. Because of using small value of reactor, its resistance is neglected.

B. Operation Principles

In normal operation of power system, self turn off switch is ON. So, R is bypassed. In addition, L_d is charged to the peak of line current and behaves as a short circuit. Neglecting small voltage drop on semiconductor devices, total voltage across FCL becomes almost zero. So, the proposed FCL doesn't affect normal operation of power system.

As fault occurs, line current starts to increase. When it reaches to the pre-defined value (I_0), self turn off switch begins to switching with special frequency (f_s) and duty cycle (D). By this switching pattern, the desired value of resistor enters to the current path and limits the fault current to acceptable value.

By removal of fault, self turn off switch stops switching and the proposed FCL returns to normal state.

III. Analytical Analysis of The Proposed FCL

In this section, it will be shown that the proposed FCL can generate a controllable resistor in the fault current path.

To calculate the equation of $i_{dc}(t)$, three modes are considered as follows:

A. Pre-fault condition (Until t_f in Fig. 2)

B. Fault duration before self turn off switch operation (From t_f to t_{off} in Fig. 2)

C. Fault duration after self turn off switch operation (From t_{off} to time of fault removal in Fig. 2)

A. Pre-fault condition

In pre-fault condition, $i_{dc}(t)$ is equal to peak of line current (I_{peak}). Also, L_d is charged and operates as a short circuit. As mentioned in previous section, because of small value of dc reactor, its resistance is neglected. So, FCL does not affect normal operation of power system.

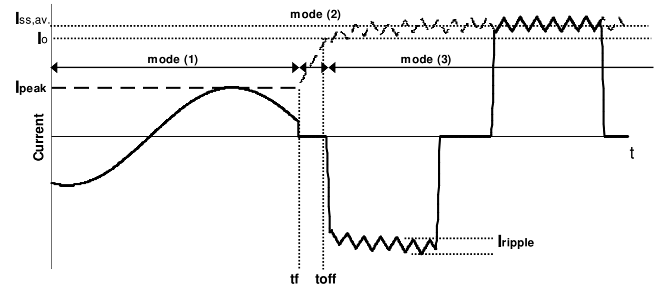

Fig. 2. — — dc reactor current ——— Line current (A phase)

B. Fault duration before self turn off switch operation

Considering Fig. 2, fault occurs at t_f and L_d starts to charge. At t_{off}, $i_{dc}(t)$ reaches to I_0. This mode is between t_f and t_{off}. Differential equation of $i_{dc}(t)$ can be expressed by:

$$V_{Ds} = L_d \frac{di_{dc}(t)}{dt} \tag{1}$$

$$i_{dc}(t = t_f) = I_{peak} \tag{2}$$

$$V_{Ds} = \frac{6}{\pi}\sin(\frac{\pi}{3})aV_m \tag{3}$$

Where, V_m, V_{Ds} and a are the peak of isolation transformer secondary side voltage, rectified voltage by three phase diode rectifier bridge and the isolation transformer windings ratio, respectively. As a result, we have:

$$i_{dc}(t) = \frac{V_{Ds}}{L_d}(t - t_f) + I_{peak} \tag{4}$$

C. Fault duration after self turn off switch operation

To calculate the self turn off switch operation instant (t_{off}), Eq. (4) is equated to I_0. So, we have:

$$I_0 = \frac{V_{Ds}}{L_d}(t_{off} - t_f) + I_{peak} \tag{5}$$

then:

$$t_{off} = t_f + \frac{L_d}{V_{Ds}}\left(I_0 - I_{peak}\right) \tag{6}$$

From t_{off}, self turn off switch starts switching. At this interval, average of steady state dc current can be expressed by:

$$I_{ss,av.} = \frac{\frac{2V_{Ds}}{R}\left\{1 - e^{-\frac{R}{L_d}(1-D)T_s}\right\} + \frac{V_{Ds}}{L_d}DT_s\left\{1 + e^{-\frac{R}{L_d}(1-D)T_s}\right\}}{2\left\{1 - e^{-\frac{R}{L_d}(1-D)T_s}\right\}}$$

(7)

By simplifications (assume that f_s has large value.), Eq. (7) can be simplified to Eq. (8) as follows:

$$I_{ss,av.} = \frac{V_{Ds}}{R(1-D)} \quad (8)$$

Equation (8) shows that the value of $I_{ss,av.}$ depends on D. It means that by controlling D, it is possible to change the value of $I_{ss,av}$. Introducing R_{dc} equals to $R(1-D)$, it is concluded that the duty cycle of self turn off switch results in variable and controllable resistor in dc side of the proposed FCL and consequently from power system point of view. In fact, the duty cycle of self turn off switch determines the resistor value that will appear in series with the power line. This controlled resistor value can be applied to improve the transient stability of system that will be discussed in section IV in detail.

It is important to note that considering Fig. 2, f_s affect the ripple of line current (I_{ripple}) during fault (Eq. 9).

$$I_{ripple} = \frac{V_{Ds}}{L_d} DT_s \quad (9)$$

IV. Transient Stability Analysis Using The Proposed FCL

Transient stability analysis is established on single line diagram of power system with the proposed FCL at the beginning of one of the parallel lines (Fig. 3). Before the fault, the system is operating in steady state. So, transfer power can be expressed by:

$$P_g = \left(EV/X\right)\sin\delta_0 \quad (10)$$

where:

E : RMS line to line synchronous generator voltage;
V : RMS line to line infinite bus voltage;
X : Total reactance ($X_t = X_d + X_t + X_L/2$);
X_d : Unsaturated reactance of generator;
X_t : Transformer reactance;
X_L : Line reactance;
δ_0 : Load angle.

By considering three phase fault at power line L_2 that its location is determined by the factor of k, without using the proposed FCL, the transfer power to the infinite bus will be reduced. So, it is possible that the synchronous generator be unstable. Using the proposed FCL at the beginning of the parallel lines can ensure stability of the synchronous generator. In Fig. 3, R_{ac} is the resistor of the proposed FCL that will appear in current path during fault. Fig. 4 shows the equivalent circuit during fault with the proposed FCL after applying star to delta transformation in Fig. 3.

To compute output power of generator during fault, firstly,

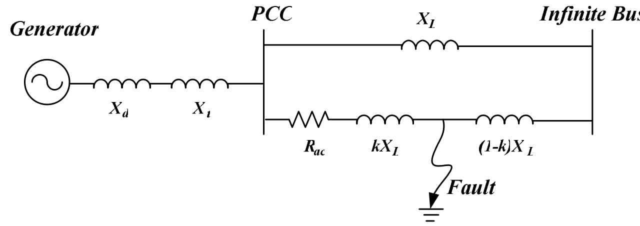

Fig. 3. Single line diagram of power system with the proposed FCL

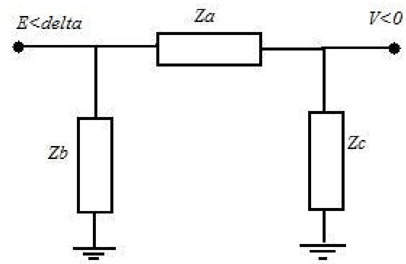

Fig. 4. Equivalent circuit during fault with the proposed FCL

we calculate output current of the synchronous generator (I_g) in Fig. 4. So we have:

$$I_g = \left(E\angle\delta/|Z_b|\angle\alpha_2\right) + \left(\left(E\angle\delta - V\angle 0\right)/|Z_a|\angle\alpha_1\right) \quad (11)$$

$$\begin{cases} Z_a = b + c + \left(bc/a\right) \\ Z_b = a + c + \left(ac/b\right) \\ a = Z_F + \left(j(R_{ac} + jkX_L)X_L/(R_{ac} + j(2X_L + kX_L))\right) \\ b = -X_L^2/(R_{ac} + j(2X_L + kX_L)) \\ c = jX' + \left(j(R_{ac} + jkX_L)X_L/(R_{ac} + j(2X_L + kX_L))\right) \\ X' = X_d{}' + X_t \end{cases} \quad (12)$$

Where Z_F and $X_d{}'$ are fault impedance and unsaturated transient reactance, respectively. Considering three phase fault, Z_F is equal to zero, approximately. So during fault, output power of the synchronous generator can be expressed by:

$$P_f = real(I_g{}^* E\angle\delta) = \left(E^2/|Z_a|\right)\cos\alpha_1 + \left(E^2/|Z_b|\right)\cos\alpha_2 + \left(EV/|Z_a|\right)\sin(\delta + \alpha_1 - \pi/2) \quad (13)$$

Considering Eq. 13, it is obvious that power of the synchronous generator depends on the value of resistor in ac side of the proposed FCL (R_{ac}) during fault. To reach the maximum transient stability the optimal value of R_{ac} must be calculated. It is important to note that the value of R_{ac} is different with the value of resistor in dc side of the proposed FCL (R_{dc}). To compute the relation of R_{ac} and R_{dc}, the active powers in ac and dc side of the proposed FCL must be equated. So, we have:

$$P_{ac} = P_{dc} \quad (14)$$

$$3\frac{\left(V_m/\sqrt{2}\right)^2}{R_{ac}}=\frac{\left(\frac{6}{\pi}\sin(\frac{\pi}{3})aV_m\right)^2}{R_{dc}} \qquad (15)$$

As a result:

$$R_{dc}=\left(\frac{18a^2}{\pi^2}\right)R_{ac} \qquad (16)$$

V. Optimum Resistor Calculation

During fault, the proposed FCL can insert resistor in fault current path to consume the excessive energy of fault. Considering Fig. 3, the consumed active power of resistor (P_{fcl}) can be expressed by:

$$P_{fcl}=\frac{V_{PCC}^2 R_{ac}}{R_{ac}^2+k^2X_L^2} \qquad (17)$$

where V_{PCC} is point of common coupling voltage

To achieve minimum rotor speed or maximum transient stability, the optimum value of resistor must be chosen. To calculate this optimum value, the synchronous generator active power should be equated with pre-fault condition active power, during fault. Because of same characteristics of parallel lines, transfer power of each line is considered equal before fault. So, considering Eq. 10 and 17, we have:

$$\frac{V_{PCC}^2 R_{ac,opt}}{R_{ac,opt}^2+k^2X_L^2}=\frac{P_g}{2}=\frac{EV}{2X}\sin\delta_0 \qquad (18)$$

As a result:

$$R_{ac,opt}=\frac{V_{PCC}^2+\sqrt{V_{PCC}^4-P_g^2k^2X_L^2}}{P_g} \qquad (19)$$

From Eq. 19, it is obvious that $R_{ac,opt}$ depends on P_g and k . To show the effect of P_g and k on the value of $R_{ac,opt}$, variations of these parameters must be analyzed.

A. Influence of the fault location on optimum resistor value

Fig. 5 shows the variation of $R_{ac,opt}$ respect to k . In this figure, P_g is parameter. Fig. 5 shows this fact that with variation of k from 0 to 1, the value of $R_{ac,opt}$ dose not change in considerable range. So, it can be concluded that the fault location is not important from $R_{ac,opt}$ value point of view.

B. Influence of the pre-fault active power of synchronous generator on optimum resistor value

Fig. 6 shows the variation of $R_{ac,opt}$ respect to P_g . The parameter of this figure is k . This figure shows that for a wide range of pre-fault condition active power (0.4 to 0.8 p.u.), the optimal resistor value changes in a wide range.

In practice, considering power demand, the active power variation is not unexpected in power lines. So, using a controllable resistor will be important.

The proposed FCL is capable to insert a variable and controllable resistor in current patch. According to above mentioned discussion, to compute the optimal resistor value, the pre-fault condition active power is considered and the k factor is assumed 0.5. It means that fault occurs in middle of line. Fig. 7 shows the control circuit of the proposed FCL. Considering Fig. 7, to achieve the optimum value of resistor, the active power is measured online in normal condition and duty cycle is obtained. In such condition, when fault occurs, the self turn off switch starts switching with a specified frequency and obtained duty cycle and the optimum resistor enters to the fault current patch from power system point of view. So, the synchronous generator will had maximum stability and the rotor speed oscillation will be reduced.

In addition, the optimum value of resistor that is highlighted in Fig. 5 and 6 is used in simulation section.

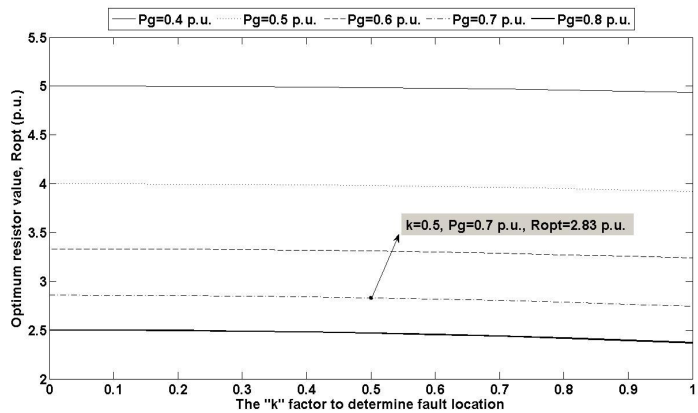

Fig. 5. Optimum resistor variation respect to k

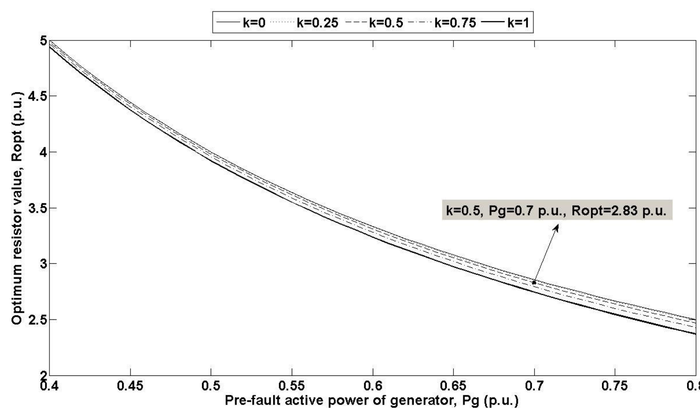

Fig. 6. Optimum resistor variation respect to P_g

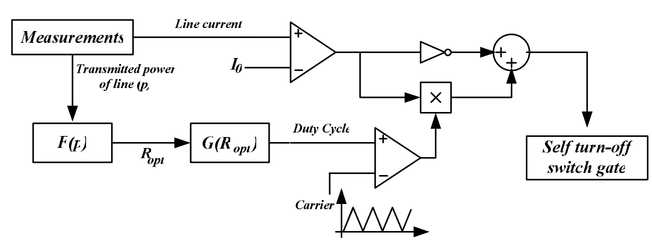

Fig. 7. Control circuit of the proposed FCL

VI. SIMULATION RESULTS

Simulation using PSCAD/EMTDC software is performed on Fig. 3. Table I shows the parameters of simulation.

To study the performance of proposed FCL on current limitation and transient stability improvement, a three-phase fault is considered at $t = 15s$ with duration of $0.2s$ (10 cycles of power frequency).

Fig. 8 shows the current of faulted line by using the proposed FCL which has optimum value of resistance. This figure shows that the fault current is limited properly.

Fig. 9 shows the synchronous generator current without using the proposed FCL. This figure shows that in such condition, the generator becomes unstable. By using the proposed FCL, current of generator is limited and the stability of generator is guaranteed as shown in Fig. 10. Voltages of the synchronous generator terminal without and with the proposed FCL are shown in Fig. 11 and 12, respectively. As shown in these figures, without using FCL, voltage of generator terminal drops strongly and then, generator becomes unstable. However, by using the proposed FCL, voltage is restored.

To prove the accuracy of analysis on optimum resistor calculation, the rotor speed response of generator for several values of resistor is shown in Fig. 13. The best response of rotor speed (lowest oscillations) is for the duty cycle that leads to optimum value of resistor.

In addition, effect of the proposed FCL on the transmitted power through parallel line is shown in Fig. 14 and 15. Without using the proposed FCL, the active power of healthy line oscillates severely because of the synchronous generator instability (Fig. 14). By using the proposed FCL, healthy line is not affected by fault as shown in Fig. 15.

By $D = 35\%$, 55% and 75% for the self turn off switch, the resistance values that will be appear in series with the fault current pass are 3.95p.u., 2.83p.u. (optimum value) and 1.52p.u., respectively. Note that, 2.83p.u. for optimum resistor value is 10.2Ω. Considering Eq. (16), R_{dc} is calculated 18.25Ω and therefore, considering that $R_{dc} = (1 - D)R$, duty cycle is obtained 55%, approximately.

Table I. Simulation parameters

Power system parameters	***Generator***	4 poles, 380V, L-L RMS, 50Hz, $S_b = 40kVA$, $P_m = 0.7\,p.u.$ $X_d = 1.227\,p.u.$, $X'_d = 0.394\,p.u.$
	Transformer data	380/380 V, $50kVA$, $X_t = 0.00145H$
	Infinite bus	400V, L-L RMS
	Transmission lines	$X_L = 0.0064H$
FCL data	***dc side parameters***	$R = 40\Omega$, $L_d = 0.03H$ $V_{DF} = V_{SW} = 1V$, $f_s = 1kHz$
	Isolation transformer parameters	$50Hz$, $5kVA$, $a = 1$

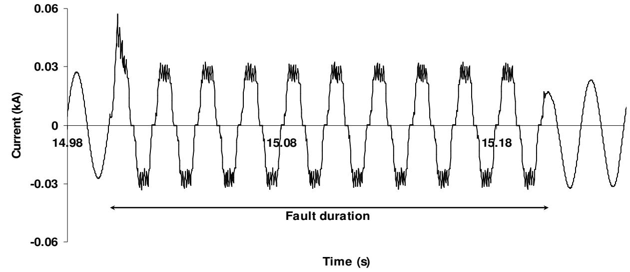

Fig. 8. Current of faulted line by using the proposed FCL

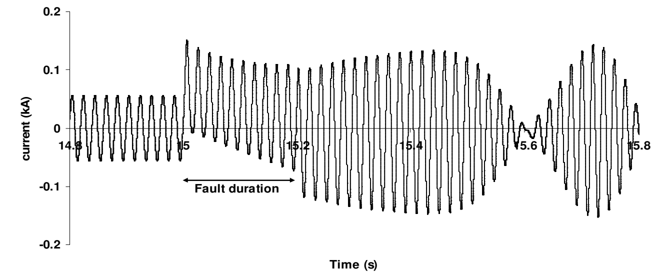

Fig. 9. Generator current without using the proposed FCL

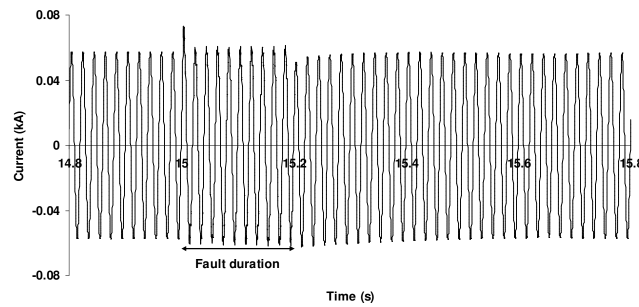

Fig. 10. Generator current with the proposed FCL

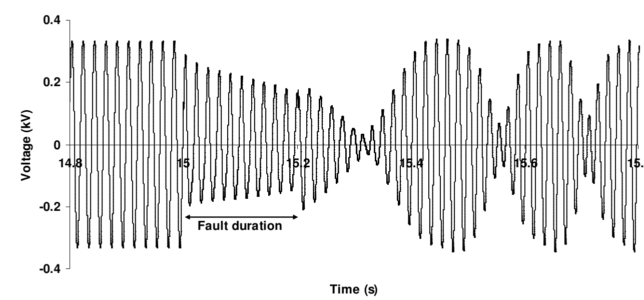

Fig. 11. Generator terminal voltage without the proposed FCL

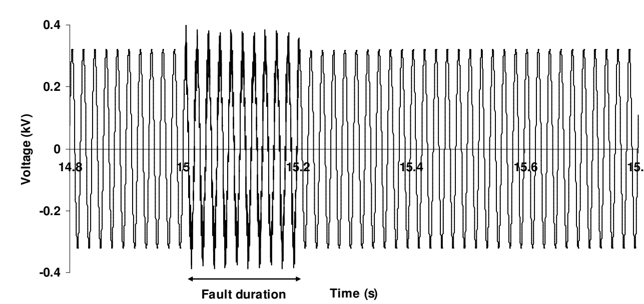

Fig. 12. Generator terminal voltage with the proposed FCL

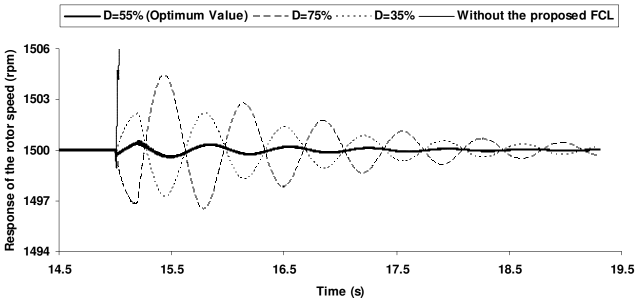

Fig. 13. Rotor speed oscillations of the synchronous generator

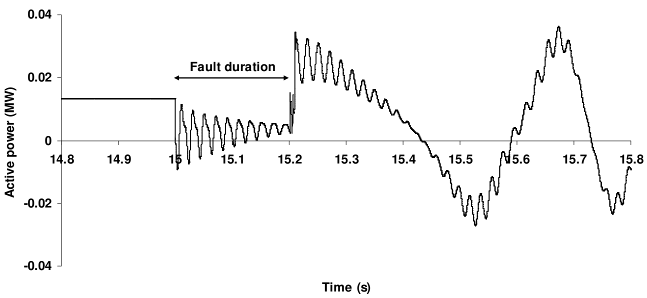

Fig. 14. The active power of healthy line without using the proposed FCL

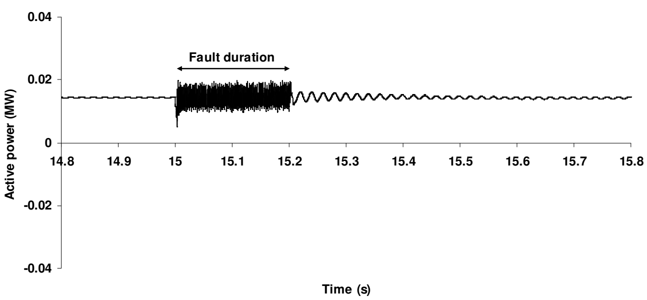

Fig. 15. The active power of healthy line using the proposed FCL

VII. Conclusion

In this paper, a controllable resistor type FCL for improvement of power system transient stability is introduced. From transient stability point of view, exact value of resistor during fault is important. On the other hand, discussions related to effect of fault location in line and pre-fault active power of the synchronous generator on the optimum value of resistor are presented and it is concluded that the optimum value of resistor mostly depends on pre-fault active power of generator. However, because of generator power changing considering power demand, optimum value of resistor is not constant. The proposed FCL with a simple control method can insert exactly this optimum value of resistor to the utility considering generator active power changing. In general, analytical analysis and simulation results using PSCAD/EMTDC software show that the proposed FCL has good flexibility for transient stability improvement in addition to fault current limiting.

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