Impact of Bridge type Fault Current Limiter on Power System Transient Stability

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Abstract

In this paper, transient stability improvement using bridge type fault current limiter (FCL) is presented in single machine infinite bus (SMIB) system with a double circuit transmission line. Three single-phase sets of the proposed FCL are installed at the beginning of feeder. The proposed FCL inserts an inductance and a resistance in the fault current pass. The insertion inductance and resistance not only limits the fault current level in an acceptable value but also improves transient stability of power system by consuming excessive energy of synchronous generator during fault. To reach maximum transient stability, the optimal resistor value of the proposed FCL is calculated. Analytical analysis and simulation results using PSCAD/EMTDC software are presented to show the current limiting future and transient stability enhancement using the proposed FCL in SMIB.

Keywords-transient stability improvement; fault current limiter; optimal resistor; semiconductor switch.

1. INTRODUCTION

Two of the most important design considerations for power systems are transient stability and damping of electromechanical modes of sustained oscillation. These two design considerations have assumed even greater importance in the wake of recent interconnection blackouts in the U.S., Canada, and Europe. So, the transient stability plays an important role for maintaining security of power system operation [1-3].

Due to the importance of transient stability improvement, different methods are introduced in literature for this purpose, such as power system stabilizer (PSS), breaking resistor, superconducting magnetic energy storage (SMES) and flexible AC transmission (FACTs) devices [4-8].

As another solution, fault current limiters (FCLs) can improve the transient stability of the power system by suppressing the level of fault currents in a fast and effective manner. The FCL which is capable of consuming the active power can be applied to the enhancement of the power system transient stability by absorbing the accelerating power of synchronous generator during fault. On the other hand, optimum value of FCL's resistance is important from the transient stability point of view [9-12].

One group of these structures is R-type superconducting FCLs (RSFCLs). The RSFCLs limit the fault current by using resistance and consume the excessive energy of synchronous generator during fault [12-14]. However, the FCLs which use superconductor (SFCLs) have two main problems. The main problem is high construction and high maintenance cost of superconductors. So, these devices are not commercially available. In addition, the resistance of RSFCL is not constant during the fault due to its quenching characteristics [12]. So, determination of the optimal resistor value of these FCLs is difficult slightly.

In [14] and [15], the transient stability improvement of the power system is presented by use of the SFCL in parallel with a resistor in series with a ZnO device. The mentioned FCL's impedance is inductive type (because of using superconductor) and resistive type. Using inductance can limits ac components of fault current better than R-type of FCLs. In these structures, two cases must be considered:

1) Insertion the optimal resistor value during fault
2) High construction and maintenance cost of superconductors

Above mentioned cases are important from both the transient stability and commercial point of view.

In this paper, the proposed FCL inserts an inductance and a resistance to improve the transient stability of power system in addition to fault current limiting. The inductive part of the proposed FCL's impedance limits ac components of fault current and the resistive part not only limits the fault current, but also consumes the excessive energy of the synchronous generator without using any superconductor. So, the proposed FCL can improve transient stability of the power system. To calculate the optimal resistor value to reach maximum transient stability, analytical analysis is presented in detail. Simulation results using PSCAD/EMTDC software is provided considering the proposed FCL with the optimal resistor value.

2. POWER CIRCUIT TOPOLOGY OF THE PROPOSED FCL AND ITS OPERATION

Fig. 1 shows the power circuit topology of the proposed FCL which is composed of two following parts:

1. Bridge part that includes a diode rectifier bridge, a small dc limiting reactor (L_{dc}), a semiconductor switch (IGBT or GTO), a free wheeling diode (D_5).
2. Main part: shunt branch which consists of a resistor and an inductor ($R_{sh} + j\omega L_{sh}$).

In the normal operation of power system, the semiconductor switch is ON and the L_{dc} is charged to the peak of the line current, therefore behaves as a short circuit. Using

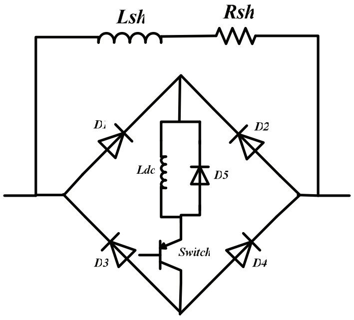


Fig. 1. Power circuit topology of the proposed FCL

semiconductor devices (the diodes and the semiconductor switch) and small dc reactor, cause a small voltage drop on the proposed FCL that it is negligible. So, the proposed FCL does not affect the normal operation of the power system.

Because of small value of L_{dc}, it can be designed with air core to prevent its saturation.

As a fault occurs, the line current begins to increase, but the L_{dc} limits its increasing rate and protects semiconductor switch against severe di/dt at the beginning of fault occurrence. When the current reaches to the maximum permissible fault current, I_m, which is specified by operator, control system of the semiconductor switch turns it off. So, the bridge retreats from feeder and shunt impedance enters to the faulted line and limits fault current and consumes excessive energy of synchronous generator during fault. At this moment, the free wheeling diode discharges L_{dc}. In fact, free wheeling diode is used to provide free route for dc reactor current when the semiconductor switch is off.

After fault removal, the semiconductor switch turns on again and the proposed FCL returns to the normal state.

3. Transient Stability and Optimal Resistor Calculations

The power system of Fig. 2 is used for transient stability calculations. The proposed FCL is installed at the beginning of the most exposed power line. In addition, parallel lines have same characteristics. In the normal operation of power system, the output power of synchronous generator can be expressed as follow:

$$P_g = (EV/X)\sin\delta_0 \tag{1}$$

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.

Three phase faults are the worst fault conditions which makes the transmitted power zero in faulty line, approximately. So, the synchronous generator becomes unstable, probably. Considering Fig. 2, if three phase fault occurs in point of common coupling (PCC), the output power of synchronous generator reaches near to zero. The proposed FCL inserts the impedance which includes the resistor and the inductance in fault current path. So, the proposed FCL not only restores the PCC voltage and the transmitted power of healthy line, but also ensures the transient stability of the synchronous generator by consuming excessive energy of fault.

Fig. 3 shows star-delta equivalent circuit of Fig. 2. In this condition, the generator current can be express by Eq. (2).

$$I_g = \left(E\angle\delta / |Z_b|\angle\alpha_2\right) + \left((E\angle\delta - V\angle 0)/|Z_a|\angle\alpha_1\right) \tag{2}$$

$$\begin{cases} Z_a = b + c + (bc/a) \\ Z_b = a + c + (ac/b) \\ a = Z_F + \left(j(R_{sh} + j\omega L_{sh})X_L/(R_{sh} + j(2X_L + \omega L_{sh}))\right) \\ b = -X_L^2/(R_{sh} + j(2X_L + \omega L_{sh})) \\ c = jX' + \left(j(R_{sh} + j\omega L_{sh})X_L/(R_{sh} + j(2X_L + \omega L_{sh}))\right) \\ X' = X_d' + X_t \end{cases} \tag{3}$$

Z_F and X_d' are fault impedance that is zero in three phase fault conditions approximatly and unsaturated transient reactance, respectively. The output power of generator, P_f, can be computed during fault as follow:

$$\begin{aligned} P_f &= real(I_g^{*}E\angle\delta) = \left(E^2/|Z_a|\right)\cos\alpha_1 + \left(E^2/|Z_b|\right)\cos\alpha_2 \\ &+ \left(EV/|Z_a|\right)\sin(\delta + \alpha_1 - \pi/2) \end{aligned} \tag{4}$$

It is obvious that P_f depends on the impedance of the proposed FCL. So, to reach the maximum transient stability or minimum rotor speed swing, the optimal resistor value of the proposed FCL, R_{sh}, must be calculated. In next section, it is shown that rotor speed oscillation will be minimized for the optimum resistor value.

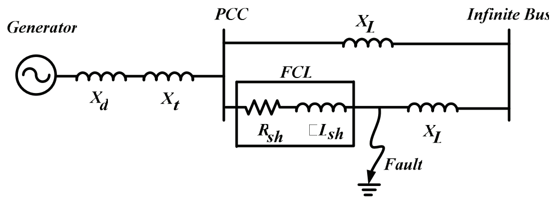


Fig. 2. The power system with the proposed FCL

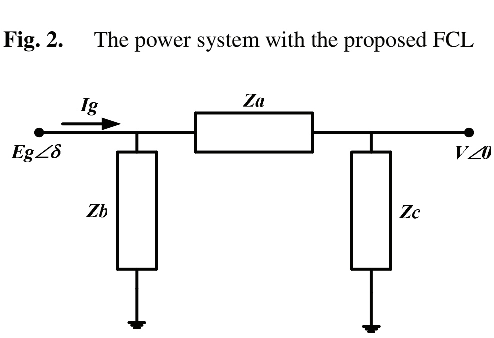


Fig. 3. Equivalent circuit of Fig. 2

To calculate the optimal value of R_{sh}, the active power of generator should be equated with pre-fault condition active power, during fault. The consumed active power of the proposed FCL, P_{fcl}, can be expressed by Eq. (5).

$$P_{fcl} = \frac{V_{PCC}^2 R_{sh}}{R_{sh}^2 + \omega^2 L_{sh}^2} \tag{5}$$

where V_{PCC} is the point of common coupling voltage (Line to Line, RMS). Because of same characteristics of parallel lines, transfer power of each line is considered equal before fault. So, considering Eq. (1) and (5), we have:

$$\frac{V_{PCC}^2 R_{sh}}{R_{sh}^2 + \omega^2 L_{sh}^2} = \frac{P_g}{2} = \frac{EV}{2X}\sin\delta_0 \tag{6}$$

As a result:

$$R_{sh,opt} = \frac{V_{PCC}^2 + \sqrt{V_{PCC}^4 - P_g^2\omega^2 L_{sh}^2}}{P_g} \tag{7}$$

where $R_{sh,opt}$ is the resistor optimal value of the proposed FCL. Considering Eq. (7), a condition must be considered as follow:

$$L_{sh} < \frac{V_{PCC}^2}{\omega P_g} \tag{8}$$

4. SIMULATION RESULTS

Transient stability improvement feature of the proposed FCL on the SMIB power system as Fig. 2 is simulated by the PSCAD/EMTDC software and its results are presented in this section. Simulation parameters are as Table 1. A three-phase short circuit fault occurs at t=15s and continues 0.2s (10 cycles of power system frequency).

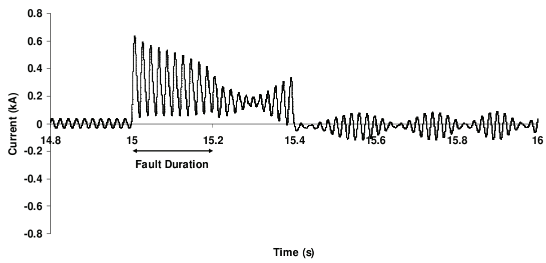
The current of faulted line (A phase current) without and with the proposed FCL are shown in Fig. 4. Fig. 4(a) shows this current without using FCL. As it is observed, the faulted line current has a very large magnitude during the fault and after fault removal; it experiences an instable condition because of the synchronous generator instability. However, by using the proposed FCL, the line current is limited during the fault and therefore, it has not instability after fault removal (Fig. 4(b)). Also, the dc side current of proposed FCL is shown in Fig. 4(b). In the normal operation, it is equal to the line current peak. As fault occurs, it is increased and after the semiconductor switch turning off, it starts to discharge by the free wheeling diode. By the fault removal and semiconductor switch turning on again, the dc current follows the line current.

Fig. 5 shows the faulted line transmitted power without and with the proposed FCL. Without using FCL, it becomes zero during fault and after fault it is distorted extremely (Fig. 5(a)). By using the proposed FCL, the power has negligible swing during and after the fault. It is obvious that the power of faulted line is near to pre-fault condition active power during fault.

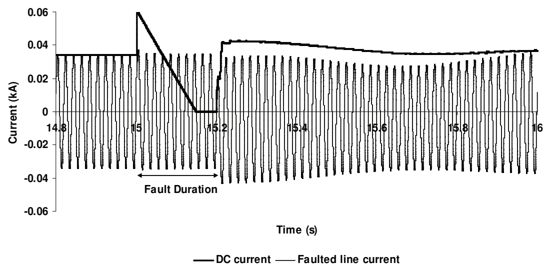
The output current of the synchronous generator is shown in Fig. 6. This figure shows the instability of generator without using the FCL and its stability by using the FCL (Fig. 6(a) and 6(b), respectively). Fig. 7 shows these results for the voltage of generator terminal. Without using the FCL, it drops extremely and after fault, it becomes instable. However, its stability is ensured by using the proposed FCL. Considering Fig. 7a, the voltage of terminal generator is restored during fault which this condition causes that the healthy line is not affected by three phase fault in the faulted line and reliability of the power system is increased.

Table 1. Simulation parameters

Power system parameters	*Generator*	4 poles,380V(L-L),50Hz $S_b = 40kVA$, $P_m = 0.8p.u.$ $X_d = 1.227p.u.$, $X'_d = 0.394p.u.$
	Transformer	380/380 V , $50kVA$, $X_t = 0.1p.u.$
	Infinite bus	400V, L-L RMS , 50Hz
	Transmission lines	$X_L = 0.7p.u.$
FCL data	$R_{sh} = 7.7\Omega$, $L_{sh} = 10mH$, $L_d = 5mH$, $V_{DF} = V_{IGBT} = 1V$, $I_m = 60A$	

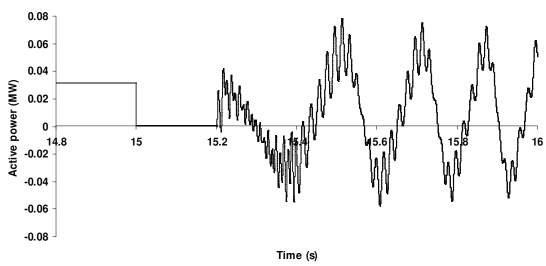


(a)

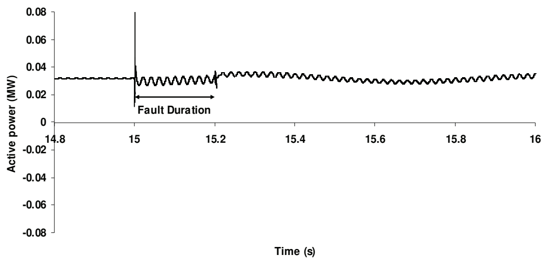


(b)

Fig. 4. Faulted line current: (a) without FCL and (b) with the proposed FCL



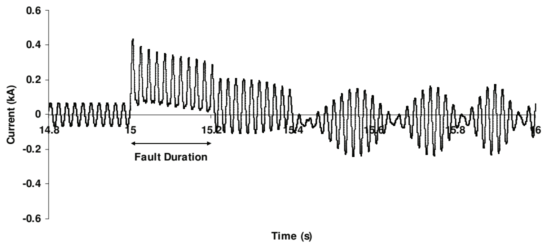
(a)



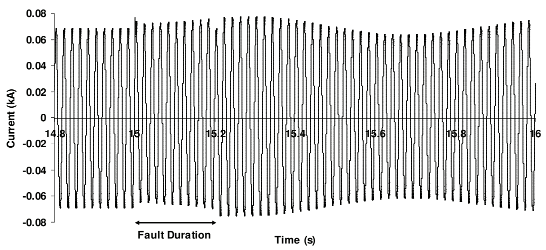
(b)

Fig. 5. Transmmited power of the faulted line: (a) without FCL and (b) with the proposed FCL

Fig. 8 shows the rotor speed oscillation of the synchronous generator caused by the fault. Without the proposed FCL, rotor speed is increased rapidly and it shows the generator instability. The optimum value of resistor for the maximum transient stability is calculated *8Ω* according to the calculations that is mentioned in section 3. The minimum swing of rotor speed is achieved for this optimum value. On the other hand, if the resistor of FCL has non-optimum value, generator's speed oscillations become larger.

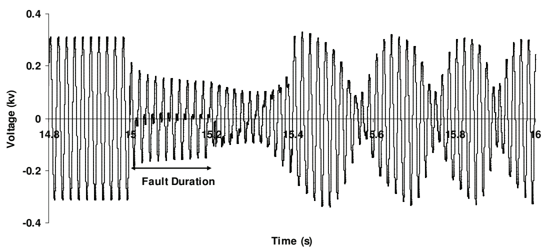


(a)

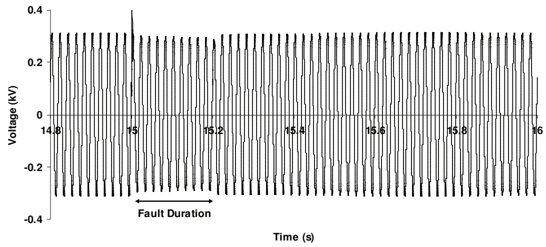


(b)

Fig. 6. Current of generator terminal: (a) without FCL and (b) with the proposed FCL



(a)



(b)

Fig. 7. The generator terminal voltage: (a) without FCL and (b) with the proposed FCL

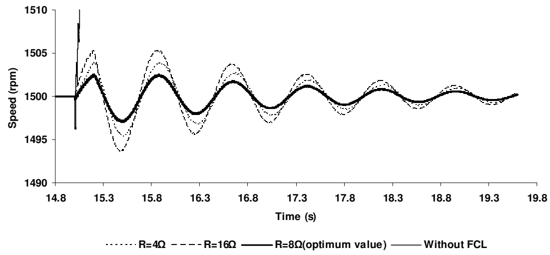


Fig. 8. Rotor speed oscillations of the generator

5. CONCLUSION

This paper proposes the FCL to improve the transient stability of synchronous generator. The proposed FCL inserts an inductance and a resistance in the fault current path. The FCL's impedance limits the fault current in an acceptable value and resistive component of the FCL consumes excessive energy of fault. Three phase fault as the worst fault condition is considered and the optimal resistor value is calculated. It is shown that the maximum transient stability will be achieved for optimal resistor value. The simulation results using PSCAD/EMTDC are presented. These results show that the proposed FCL is able to improve transient stability of power system in addition to current limiting capability.

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