TRANSIENT AND DESIGN OPERATION ASSESSMENT OF RFCL IN BULK POWER SYSTEMS

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Abstract—*The increasing capacity of power systems and the continuing growth in interconnections within transmission networks to improve the reliability may cause the short-circuit fault current level of the equipment in the system, including the existing circuit breakers, to exceed their rated capacities. Therefore, the equipment must be either upgraded or replaced, which is costly and requires time-intensive procedures. Fault current-limiting techniques offer benefits to the system in such cases. Using passive elements, such as current-limiting reactors, is a well-known practice in power systems: however, they impact the power flow under normal operation, cause voltage drop, and might reduce the transient stability. Alternatively, resonant fault current limiters (RFCL) offer a dynamic solution based on proven technologies of current-limiting reactors and series capacitors. This paper presents a comprehensive framework to design RFCLs in bulk power systems. The presented approach uses a combination of mathematical analyses and numerical time-domain simulations to design the RFCL elements, and its effectiveness is assessed in test power systems.*

Keywords— Bulk Power Systems; Fault Analysis; Network Reduction; Resonant Fault Current Limiter; Transient Stability

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1. INTRODUCTION

Demand on electricity has been increasing tremendously and many countries invest significant amount of money for reliable power supply. More generation plants and transmission lines were constructed and the power systems became more complex. Major transmission lines tend to be long-distance and generation sites are large-scaled. Load concentration requires more transmission lines to be interconnected. However, those characteristics of power systems have been causing problems related to fault currents and system stabilities. Several approaches to cope with the fault current problems are being used in distribution and transmission areas.

Permanently-inserted series reactors, up-rating and replacement of switchgear, splitting buses or transmission lines are the most commonly used techniques to limit the fault current in power systems, which are regarded as cost-effective and more secure measures for the operational reliability of power system facilities. However, up-rating and replacement of switchgear can be very expensive and short-circuit current duty may not be reduced. Network splitting can deteriorate the power system security. Permanently-inserted current-limiting series reactors introduce a voltage drop, active and reactive power losses and also adversely affect the power system stability. In spite of these drawbacks, a lot of power systems are still divided into several subsystems to solve fault current problems.

For the power system stability enhancement, on the other hand, the following has been used as countermeasures in general: (1) Constructing more interconnection lines, (2) Installing dynamic reactive resources, (3) Constraining power transfers, and (4) Using Special Protection Schemes (SPS).

2. FAULT CURRENT LIMITER (FCL) CONCEPTS

The aforementioned technologies are fault current interruption devices with fault current limiting features. Alternatively, fault current limiter (FCL) is another solution to the fault current crisis. Instead of interrupting the fault current, which usually needs to wait for the next zero crossing of current, an FCL inserts high impedance to the power line almost immediately after the fault occurrence and limits the fault current at a low level. During normal operations, the impedance is kept low enough to be negligible to the system. For more than two decades, various approaches in FCL technology have been explored. Research has provided classifications and insights to the FCL concepts in prior-art. In general, the FCL technologies can be classified into the following categories:

i. Superconducting FCL
ii. Solid-state FCL
iii. Magnetic FCL

The categorization is based on the major techniques used by FCL’s. Each of these techniques (solid-state switches, superconductors, magnetic, etc.) has their own characteristics that can provide favorable performance or features to the FCL. On the other hand, each of them has their own drawbacks or technical challenges. In this context, a number of different derivations of FCL topologies combining techniques have been studied and developed.

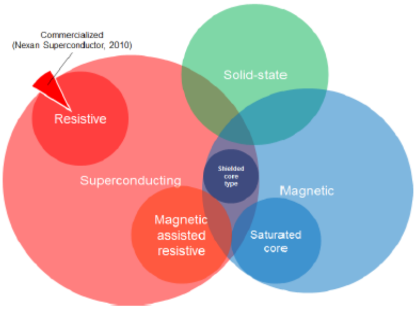

Fig. 2.1. Different types of FCL technologies and their relationships

It should be noted that although FCL's have been studied in the labs for more than two decades, it is a relatively new field in terms of R&D and applications. Multiple topologies have been proposed, but only a few have been put into field tests. Therefore, there is no "prevailing" topology: new possible solutions are still being explored and tested. Figure 2.12 illustrates the most recognized FCL technologies and the relationships among them. Figure 2.12 implies that the borderlines among FCL types are vague. For example, the superconductor in a resistive type superconducting FCL is used in a substantially different way from a saturated-core FCL does. The design constraints for superconductors in both FCL types are different, although sometimes they are both called "superconducting FCL's". Hence, in some circumstances, the aforementioned classification of FCL's could be confusing. So instead of reviewing the FCL technologies by categories, we will review the desired characteristics that each technique can provide, and analyze the major technical challenges they face in FCL implementations. Also, some topologies that have gained more attention in the FCL community will also be reviewed and analyzed.

2.1 Superconducting fault current limiters (SCFCL)

Superconductors are widely adopted in FCL topologies, mostly because they offer superior performance by presenting negligible normal operation impedance, when the temperature and magnetic field on them are below critical values. Besides, superconductors can also provide inherent fast current limiting characteristics and repetitive operation with auto-recovery.

2.2 Introduction to superconductivity

Superconductivity is the characteristic of zero resistivity and expulsion of magnetic fields in certain materials when they are refrigerated blows certain temperature levels (mostly referred to as critical temperature or transition temperature). Superconductivity phenomenon was first discovered by Dutch physicist H. Kamerlingh Onnes in his laboratory at Leiden University, Netherlands in 1911, when he managed to liquefy helium and bring the temperature of mercury to near absolute zero. In more than a century since mercury's superconductivity phenomenon was discovered, other superconducting materials with various critical temperatures have been found. Among these materials, some has been put into practical use in specific realms.

3. SYSTEM MODELING OF FCL

Fault current reduction using passive elements, such as current-limiting reactors, is a well-known practice especially in low-voltage (LV) systems. However, they have some drawbacks in high-voltage (HV) transmission networks, such as impacting the power flow under normal operation, causing voltage drop and risk of voltage collapse, and having an adverse impact on the transient stability of power systems.

3.1 STRUCTURE AND OPERATIONAL PRINCIPLE OF A RESONANT FCL

Figure 3.1 illustrates the structure of an RFCL in one of the three phases. The series resonant circuit
consists of a current-limiting reactor and a resonant capacitor which are tuned to the rated frequency of the power system to minimize the influence of the RFCL under normal operation. It is not practically possible to perfectly tune a resonant circuit and, thus, little phase shift is unavoidable.

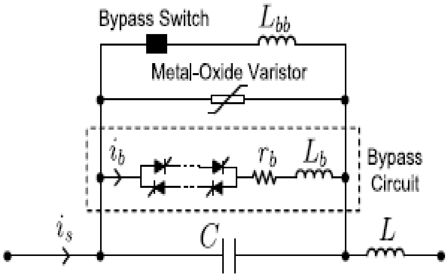

Fig-3.1. Structure of a resonant fault current limiter in one phase.

The figure also depicts that a thyristor-controlled bypass circuit, a metal–oxide varistor, and a bypass switch are in parallel to the capacitor.

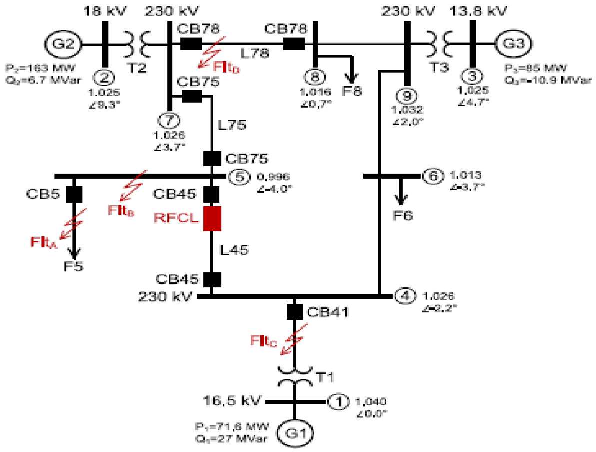

Fig. 2. Nine-bus test power system with an RFCL inserted in line L45.

As soon as a short-circuit fault is detected, the thyristor valves are triggered and the current commutates from the capacitor to the bypass circuit. Therefore, the impedance of the RFCL switches rapidly from almost zero (under normal operation) to the impedance of reactor, which prevents the development of large fault current. The fault is detected by comparing a measure of the line current, where the RFCL is located, with a predefined threshold value. Alternatively, a combination of the current magnitude and its rate of change as well as the duration of their occurrence can be used to detect a fault. The bypass circuit is based on a string of direct light-triggered thyristors in series with a discharge current-limiting reactor and a damping resistor, see Fig. 3.1; these thyristor valves have a high capability during turn-on and the possibility to operate at full potential with a simpler triggering circuit, compared to regular thyristors. The design of the bypass circuit aims to limit the rate of change of discharge current and its peak value after triggering the thyristor valves, and to reduce oscillations of the discharge current during bypass operation. The bypass circuit continues to conduct the current after fault detection.

3.2 RFCL DESIGN PROCESS

The process presented in this paper to design the elements of an RFCL and to assess its transient operation in a host power system is a combination of analytical analyses and iterative numerical simulations. Thus, an equivalent network of the overall power system, from where the RFCL is located, which accurately reproduces, during the time period of interest, the same instantaneous values of voltages and currents as those in the overall system can result in a more effective and less timely design process. The bypass circuits in the three phases of the RFCL in Fig.3.2 are triggered as soon as a fault is detected, which occurs within a quarter cycle after the fault strikes the system. Then, the current through line L45 is commutated from the resonant capacitors to the bypass circuits. Therefore, to capture the transient voltage and current stresses in the bypass circuits, in the equivalent network, it should reproduce a steady-state current through line L45, similar to that in the overall system, before the inception of the fault, and should also emulate the instantaneous line current for a quarter cycle after the strike of the fault.

3.2.1 Network Reduction

Since the RFCL is located in line L45, the aforementioned line and buses 4 and 5 at its two terminals should be retained in the final equivalent network. Also, to study the faults at feeder F5 and bus 5, it is desirable to retain bus 7 and line L75. The power-flow data can be achieved by solving power-flow equations using power systems simulation tools, such as PSSE. This model is an exact representation of the generators for the prefault steady-state condition and a close approximation for a quarter cycle after the fault strikes, which is the time period of interest required for the RFCL design. Thus, during the aforementioned time period, the state variables of the synchronous generators are assumed to remain unchanged. Moreover, all constant-power loads in the test power system are converted to their equivalent constant-admittance form, whose values are calculated based on the steady-state condition of the system before the strike of the fault. The charging capacitances of the transmission lines are also included in their equivalent models. The network reduction is carried out using the Gaussian elimination method. In this approach, the power system under study is usually divided into internal, boundary, and external systems, where the internal and boundary systems constitute the study system. In the test power system of Fig. 2, buses 4, 5, and 7 belong to the study system and should be retained and, therefore, the rest of the buses, that is, the external system, need to be eliminated to achieve the reduced network. Bus 5 is located inside the study system and buses 4 and 7 are the boundary buses.

4. SIMULATION RESULTS

To compare the transient responses of the equivalent network with and without the RFCL in line L45, to the nine-bus test system, both networks are simulated in MATLAB/SIMULINK simulation results. In the nine-bus system, dynamic models of the generators, including their exciter and governor models, are utilized, whose parameters are given.

CASE A- BYPASS AND INSERTION OF RESONANT CAPACITORS:

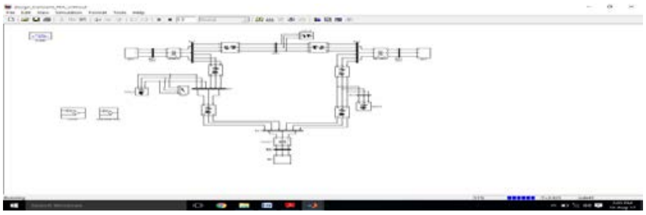

Fig:4.1 Responses of the nine-bus system to the strike of fault FltA without RFCL

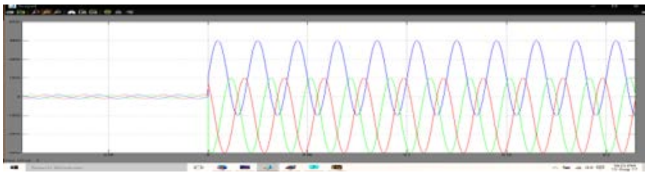

Fig:4.2 Responses of the nine-bus system to the strike of fault FltA without RFCL of a current.

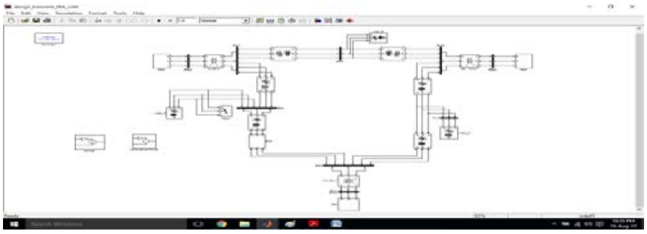

Fig:4.3 Responses of the nine-bus system to the strike of fault FltA with RFCL.

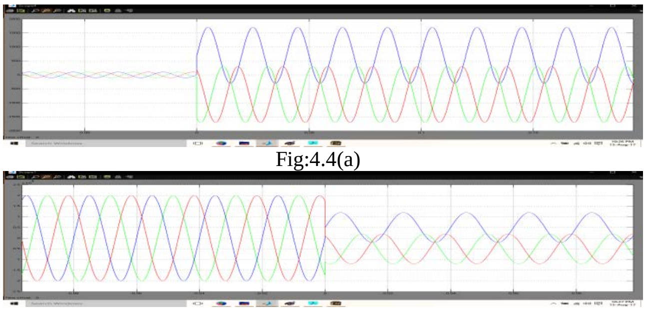

Fig:4.4(a)

Fig:4.4(b)

Fig:4.4 Responses of the nine-bus system to the strike of fault FltA with RFCL of a current and voltage.

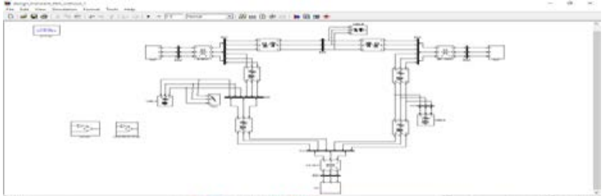

Fig:4.5 Responses of the nine-bus system without RFCL

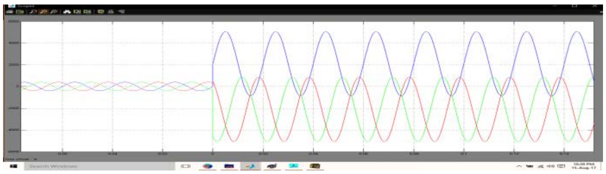

Fig:4.6 Instantaneous currents through breaker CB5 in the nine-bus system without RFCL in line L45.

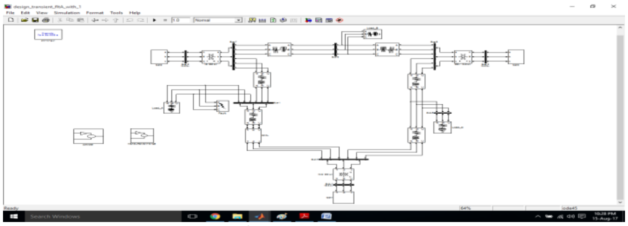

Fig:4.7 Responses of the nine-bus system without RFCL

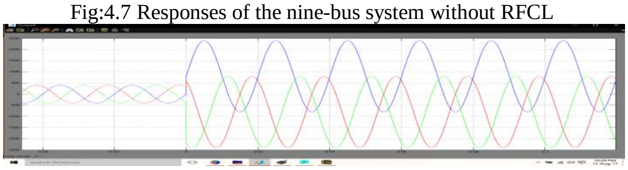

Fig:4.8 Instantaneous currents through breaker CB5 in the nine-bus system with RFCL in line L45.

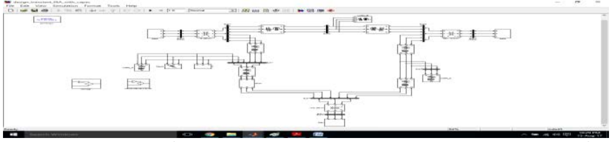

Fig:4.9 Responses of the nine-bus system to the capacitor insertion after the clearance of fault FltA.

Fig:4.10(a)

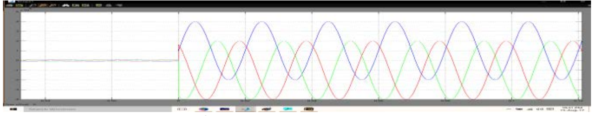

Fig:4.10(b) Responses of the nine-bus system to the capacitor insertion after the clearance of fault FltA. (a) Line currents. (b) Capacitor voltages.

5. ENERGY ABSORPTION BY VARISTORS FOR REMOTE FAULTS

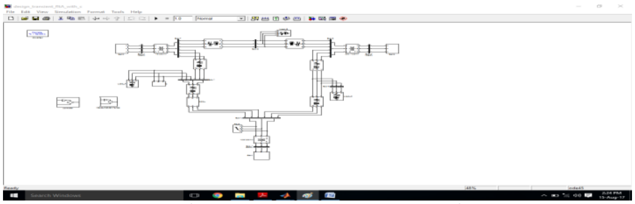

Fig:4.11 Responses of the nine-bus system to a 3LG fault at FltC and bus 4.

Fig:4.12(a)

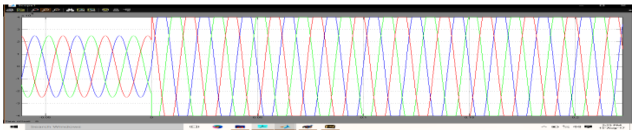

Fig:4.12(b)

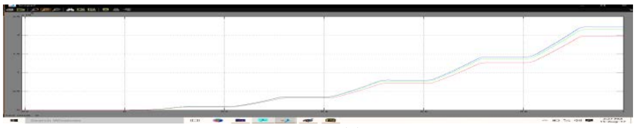

Fig:4.12(c)

Fig:4.12 Responses of the nine-bus system to a 3LG fault at FltC and bus 4. (a) Line currents. (b) Capacitor voltages. (c) Energies absorbed by the varistors.

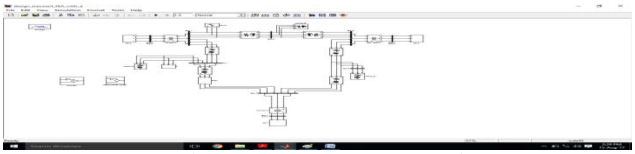

Fig:4.13 Responses of the nine-bus system to a 3LG fault at FltD and bus 7.

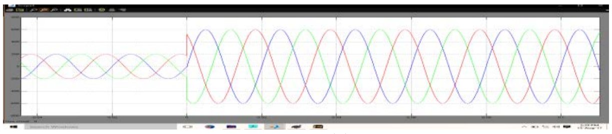

Fig:4.14(a)

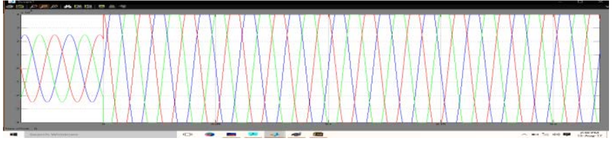

Fig:4.14(b)

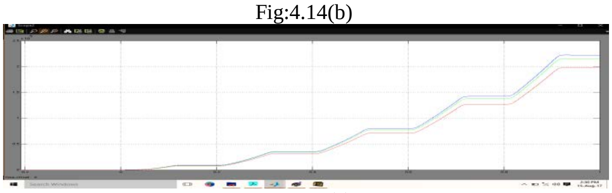

Fig:4.14(c)

Fig:4.14 Responses of the nine-bus system to a 3LG fault at FltD and bus 7. (a) Line currents. (b) Capacitor voltages. (c) Energies absorbed by the varistors.

6. FAULT CLEARANCE AND AUTORECLOSING OPERATION

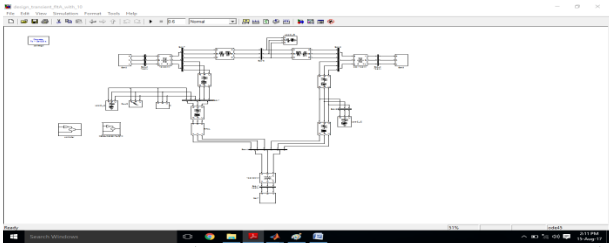

Fig:4.15 Responses of the nine-bus system subsequent to the strike of fault FltA.

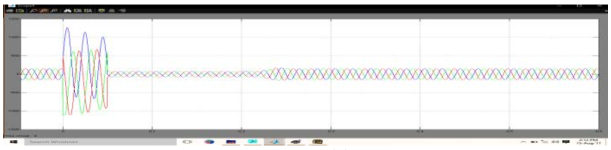

Fig:4.16(a)

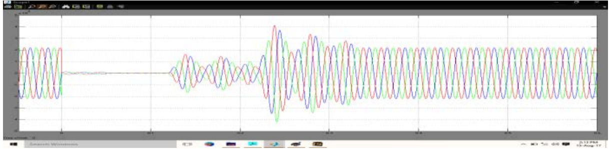

Fig:4.16(b)

Fig. 4.16. Responses of the nine-bus system subsequent to the strike of fault FltA (a) Line currents. (b) Capacitor voltages.

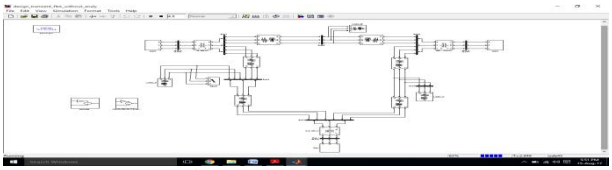

Fig: 4.17 Responses of the nine-bus system without RFCL in line L45.

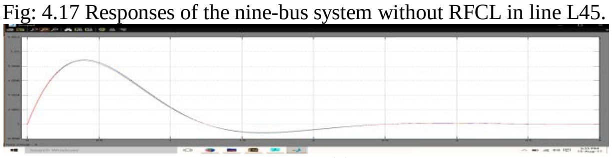

Fig:4.18(a)

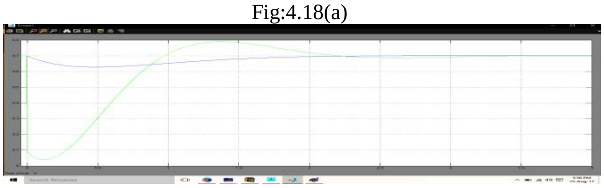

Fig:4.18(b)

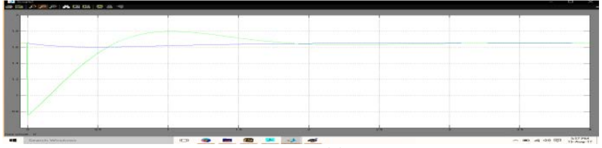

Fig:4.18(c)

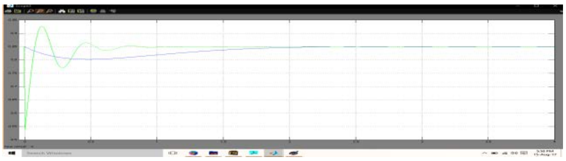

Fig:4.18(d)

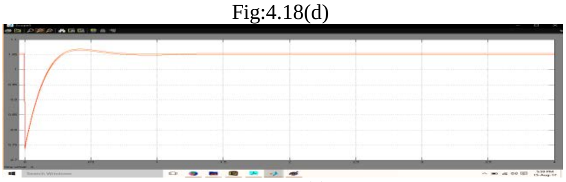

Fig:4.18(e)

Fig:4.18 Responses of the nine-bus system without RFCL in line L45. (a) Generators rotor speeds. (b)–(d) Electrical and mechanical powers of the generators. (e) Generators terminal voltages.

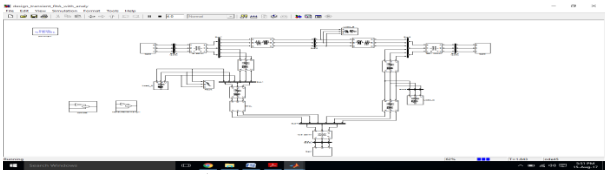

Fig: 4.19 Responses of the nine-bus system with RFCL in line L45.

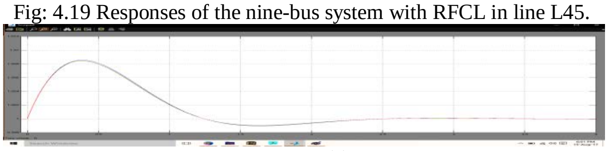

Fig:4.20(a)

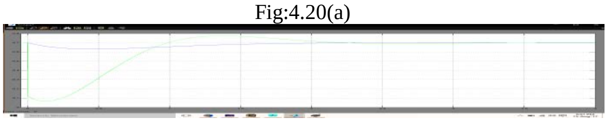

Fig:4.20(b)

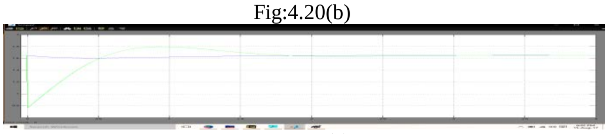

Fig:4.20(c)

Fig:4.20(d)

Fig:4.20(e)

Fig:4.20 Responses of the nine-bus system with RFCL in line L45. (a) Generators rotor speeds. (b)–(d) Electrical and mechanical powers of the generators. (e) Generators terminal voltages.

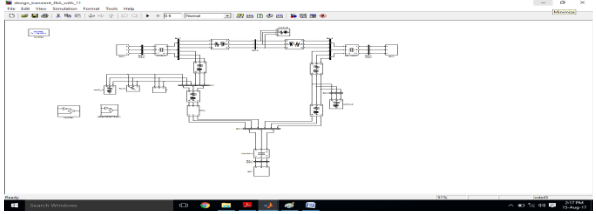

Fig:4.21 Responses of the nine-bus system subsequent to the strike of fault FltB.

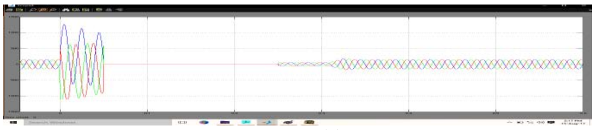

Fig:4.22(a)

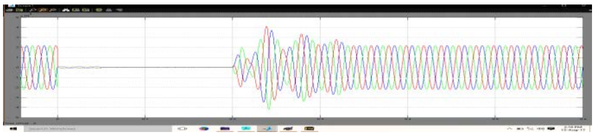

Fig:4.22(b)

Fig. 4.22. Responses of the nine-bus system subsequent to the strike of fault FltB (a) Line currents. (b) Capacitor voltages.

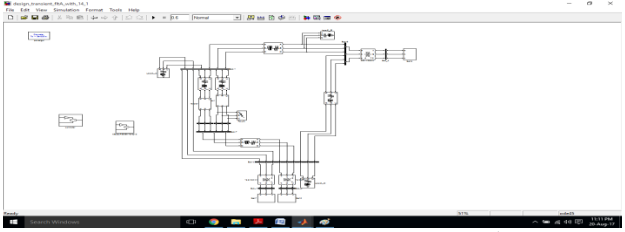

Fig:4.23 Instantaneous currents through lines L1 and L2 fixed reactors.

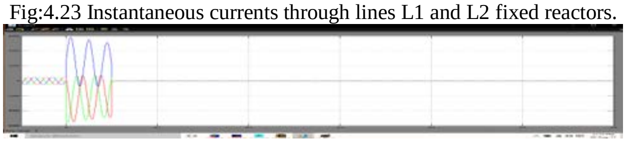

Fig:4.24(a)

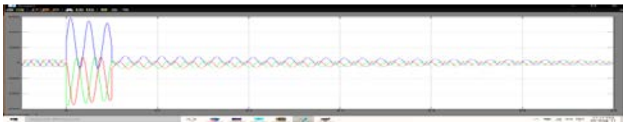

Fig:4.24(b)

Fig:4.24 Instantaneous currents through lines L1 and L2 with (a) and (b) fixed Reactors.

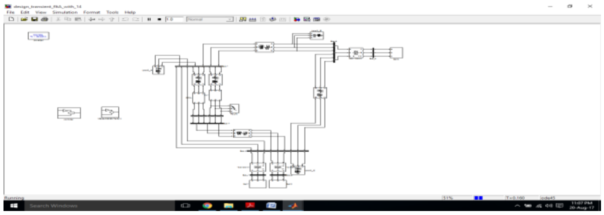

Fig:4.25 Instantaneous currents through lines L1 and L2 with RFCLs.

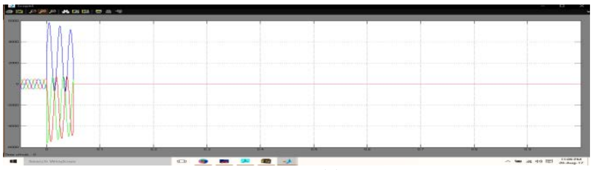

Fig:4.26(a)

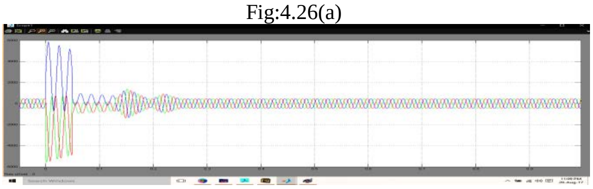

Fig:4.26(b)

Fig:4.26 Instantaneous currents through lines L1 and L2 with (a) and (b) RFCLs

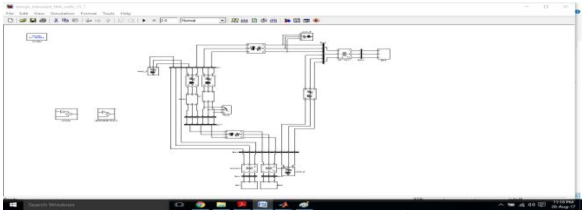

Fig:4.27 Responses of the reduced network with fixed reactors to a 3LG fault in line L1.

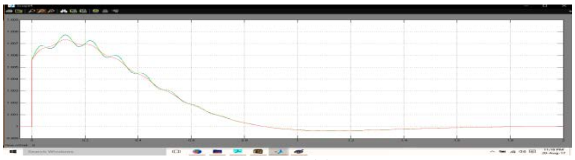

Fig:4.28(a)

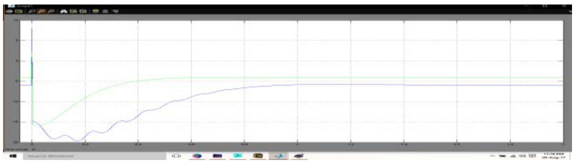

Fig:4.28(b)

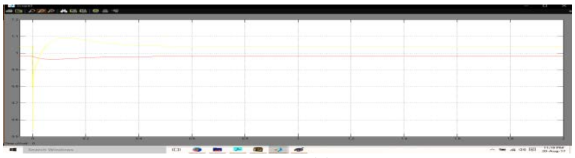

Fig:4.28(c)

Fig:4.28 Responses of the reduced network with fixed reactors to a 3LG fault in line L1. (a) Rotor speeds, (b) rotor angles with respect to G3, and (c) terminal voltages of generators.

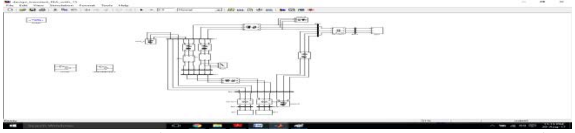

Fig:4.29 Responses of the reduced network with RFCLs to a 3LG fault in line L1.

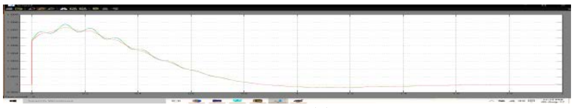

Fig:4.30(a)

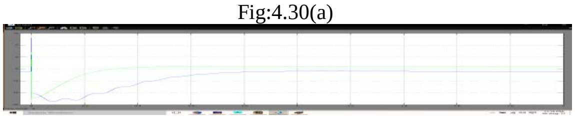

Fig:4.30(b)

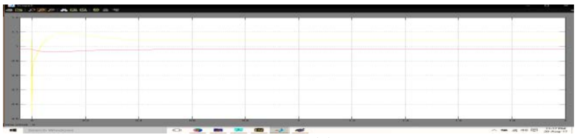

Fig:4.30(c)

Fig:4.30 Responses of the reduced network with RFCLs to a 3LG fault in line L1. (a) Rotor speeds, (b) rotor angles with respect to G3, and (c) terminal voltages of generators.

7. CONCLUSION

This paper presented a comprehensive framework to design RFCLs in bulk power systems. The elements of an RFCL were initially designed based on a combination of mathematical analyses and numerical time-domain simulations, using an equivalent network of the test power system which reproduces the instantaneous currents and voltages of the system during the time period of interest. The transient operation of the designed RFCL was then evaluated using the time-domain dynamic model of the overall test system. Finally, the framework was used in a real transmission system to design RFCLs inserted in two interconnecting lines and to assess the impact of their incorporation in the host system. It was concluded that RFCLs are effective devices for reducing the currents due to faults in bulk power systems.

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