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Improving Transient Stability of a Distribution Network by using Resonant Fault Current Limiter

SK. SHAMEEM[1], SK. NAZMA[2], CH. RAMI REDDY[3]
Dept of EEE, Nalanda Institute of Engineering and Technology, Sattenapalli, Guntur, AP, India.

Abstract: Fault current levels in electrical systems are rising due to natural growth in demand, the increasing presence of distributed generation(DG), increased network interconnection. 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 project presents a comprehensive framework to design RFCLs in bulk power systems by matlab/simulink simulation results.

Keywords: Bulk Power Systems, Fault Analysis, Network Reduction, Resonant Fault Current Limiter, Transient Stability.

I. INTRODUCTION

A fault is an unintentional short circuit, or partial short-circuit, in an electric circuit. A variety of factors such as lightning, downed power lines, or crossed power lines cause faults. During a fault, excessive current—called fault current—flows through the electrical system often resulting in a failure of one section of that system by causing a tripped circuit breaker or a blown fuse. A fault current limiter (FCL) limits the amount of current flowing through the system and allows for the continual, uninterrupted operation of the electrical system, similar to the way surge protectors limit damaging currents to house - hold devices. Currently, two broad categories of FCL technologies exist high temperature super conducting and solid-state. 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 as shown in Fig.1. Permanently-inserted series reactors, up-rating and replacement of switch gear, 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.

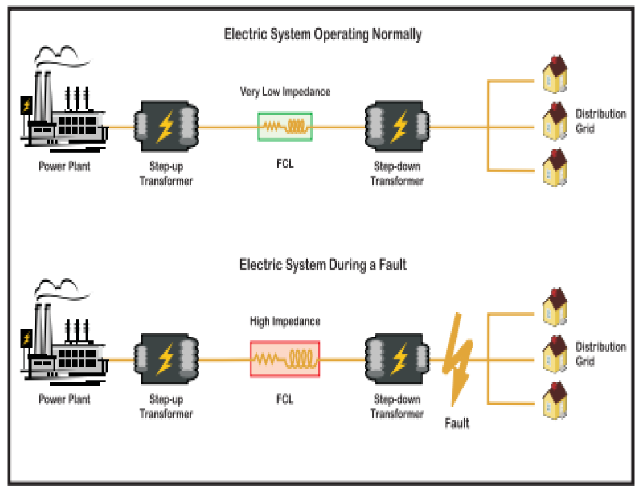


Fig.1. During a ground fault, an FCL safely mitigates the excess energy that would normally effect utility transmission and distribution equipment, preventing damage.

However, up-rating and replacement of switch gear 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. The need for FCLs is driven by rising system fault current levels as energy demand increases and more distributed generation and clean energy sources, such as wind and solar, are added to an already overburdened system. Currently, explosive fault-limiting fuses are utilized to limit fault current, but they require a service call to replace the fuse after it blows and they are only available for voltages below 35 KV but they have constant high reactive losses, are bulky, and contribute to grid voltage drops. FCLs overcome these weaknesses. Additionally, rising fault current levels increase the need for larger and often costly high impedance transformers. However, in contrast to these transformers, FCLs operate with little to no impedance during normal operation which allows for a more stable system effect utility transmission and distribution equipment, preventing damage. FCLs offer numerous benefits to electric utilities. For in - stance, utilities spends millions of dollars each year to maintain and protect the grid from potentially destructive fault currents. These large currents can damage or degrade circuit breakers and other expensive T&D system components. Utilities can reduce or eliminate these replacement costs by installing FCLs. Other benefits include:

- Enhanced system safety, stability, and efficiency of the power delivery systems
- Reduced or eliminated wide-area blackouts, reduced localized disruptions, and increased recovery time when disruptions do occur
- Reduced maintenance costs by protecting expensive downstream T&D system equipment from constant electrical surges that degrade equipment and require costly replacement
- Improved system reliability when renewables and DG are added to the electric grid
- Elimination of split buses and opening bus-tie breakers
- Reduced voltage dips caused by high resistive system components
- Single to multiple shot (fault) protection plus automatic resetting.

II. SYSTEM MODELING

Fig2 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. The figure also depicts that a thyristor-controlled bypass circuit, a metal–oxide varistor, and a bypass switch are in parallel to the capacitor. 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. 2; 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.

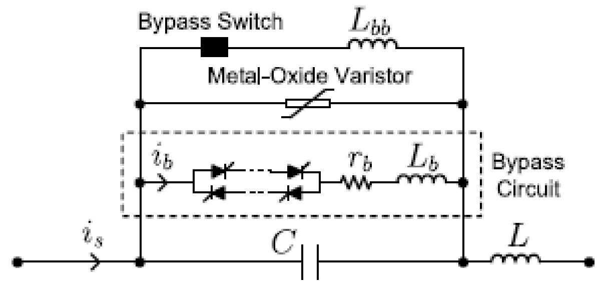


Fig.2. Structure of a resonant fault current limiter in one phase.

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. When the fault is cleared by a successful tripping of the CB located near the fault location, the firing pulses of the thyristor valves are suppressed, and the capacitor is inserted into the circuit and, thus, the RFCL impedance reduces to zero.

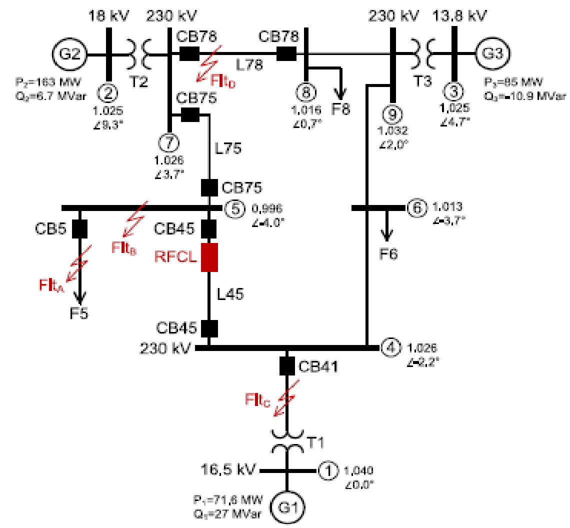


Fig.3. Nine-bus test power system with an RFCL inserted in line L45.

If the capacitor is required to remain bypassed for a longer period of time after the inception of the fault, then the bypass switch can be used to commutate the current from the bypass circuit. The inductor limits the rate of current commutation to the bypass switch. Also, the varistor should be properly rated to protect the capacitor against transient overvoltages, whenever the capacitor is not bypassed. The IEEE nine-bus test power system, whose data are given is illustrated in Fig. 3. Let us assume that breaker CB5 is properly rated for a three-phase-to-ground (3LG) solid fault at feeder F5. Similarly, let us assume that breakers CB45 are rated for a 3LG solid fault at bus 5. Now, if the interrupting capability of each aforementioned breaker is only marginally larger than the current that flows through the breaker due to a fault at feeder F5 (for CB5) or bus 5 (for CB45), then the addition of generation at bus 1, for example, in response to the installation of loads at bus 4, or in response to the growth of load at feeder F5, can prevent the breakers from interrupting the fault current. Therefore, the breakers must either be replaced or, alternatively, an RFCL can be connected in series with line L45, see Fig. 3, to limit the current through the line if faults and strike the system. This, in turn, results in a reduction in the current through breakers CB45, and, consequently, also breaker CB5, while the RFCL has a negligible impact under normal operation.

III. 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 results as shown in bellow Figs.4 to 18

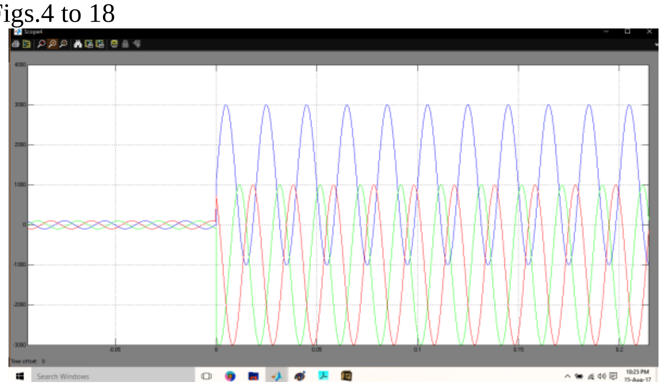
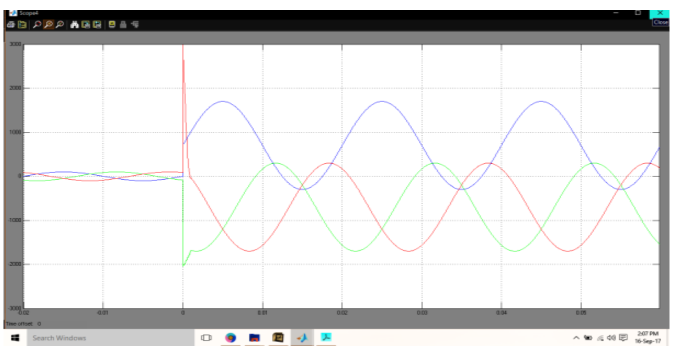


Fig.4. Responses of the nine-bus system to the strike of fault FltA without RFCL of a current.



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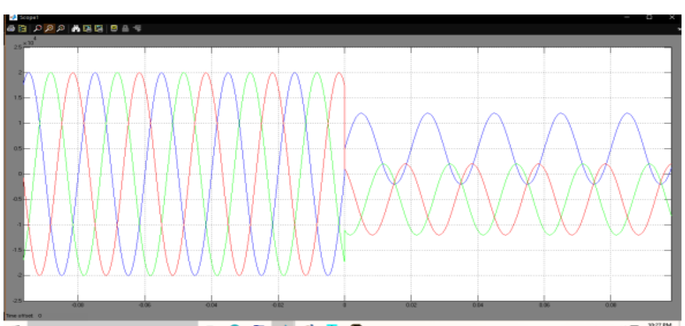


(b)

Fig.5. Responses of the nine-bus system to the strike of fault FltA with RFCL of a current and voltage.

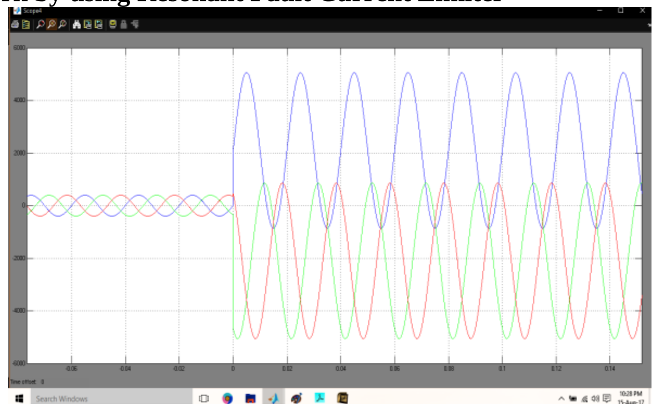


Fig.6. Instantaneous currents through breaker CB5 in the nine-bus system without RFCL in line L45.

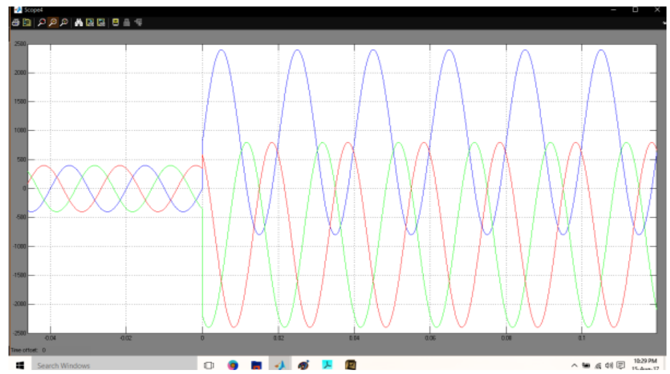
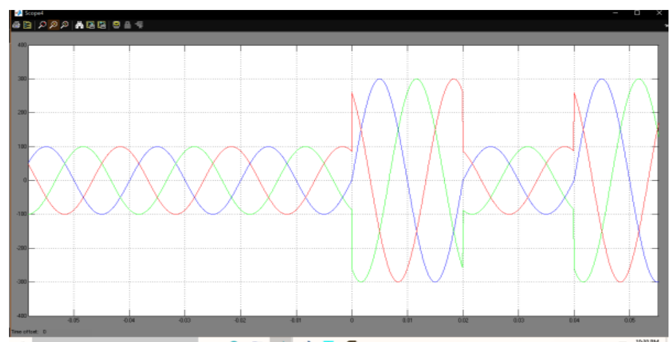


Fig.7. Instantaneous currents through breaker CB5 in the nine-bus system with RFCL in line L45.



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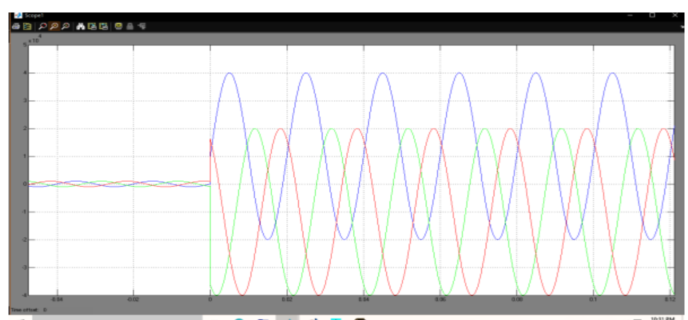

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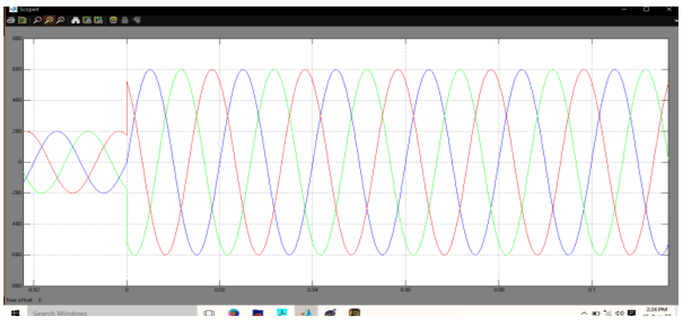
Fig.8. Responses of the nine-bus system to the capacitor insertion after the clearance of fault FltA. (a) Line currents. (b) Capacitor voltages.

It is observed that subsequent to the fault initially, the voltages across the capacitors increase due to the rise in the line current. Then, after the bypass valves are triggered, the line current commutates to the bypass circuit and the voltages across the capacitors drop. Figure plots the responses of the nine-bus test system in the two cases of without RFCL and with an RFCL in line L45, where at 0 s, fault strikes the system in each case. In the case of the RFCL, the protection-level voltage of the varistors is selected equal to two times the capacitor voltage under normal operation, that is, 43 kV, and the current threshold is equal to four times the current through line L45 under normal operation, that is, 800 A. It is observed that the responses of the nine-bus system and its equivalent network, in the two cases, are in close agreement during the prefault and a quarter cycles after the inception of the fault.



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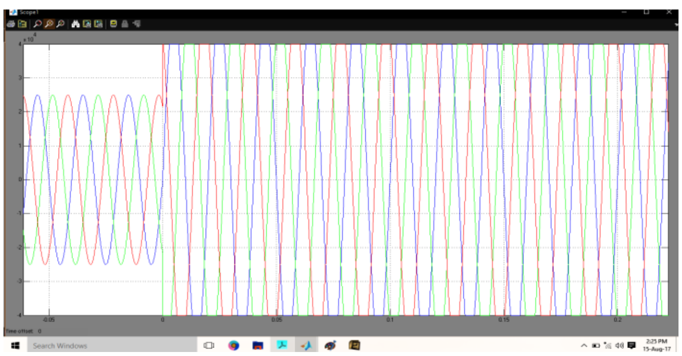

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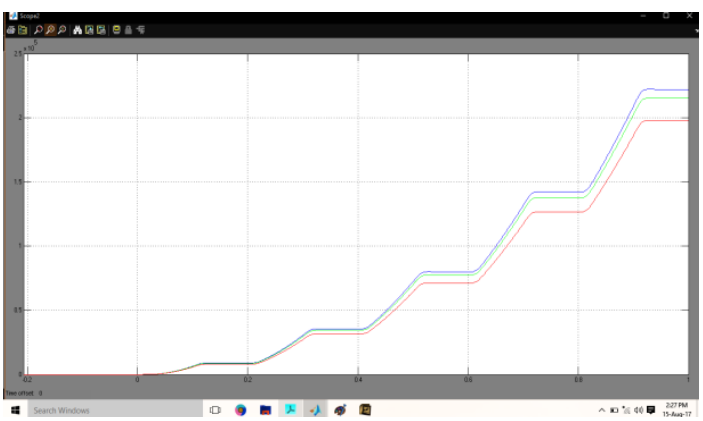

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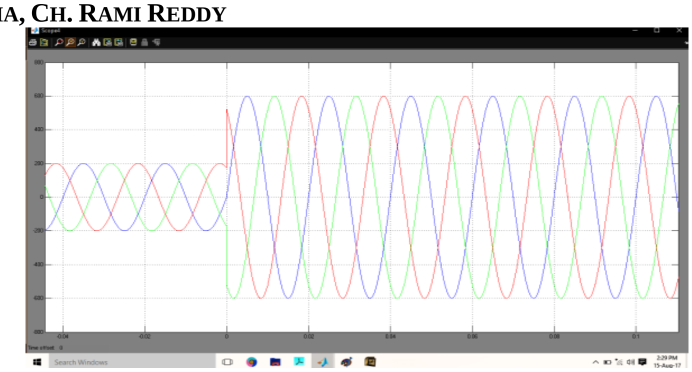
Fig.9. Responses of the nine-bus system to a 3LG fault at FltC and bus 4. (a) Line currents. (b) Capacitor voltages. (c) Energies absorbed by the varistors.



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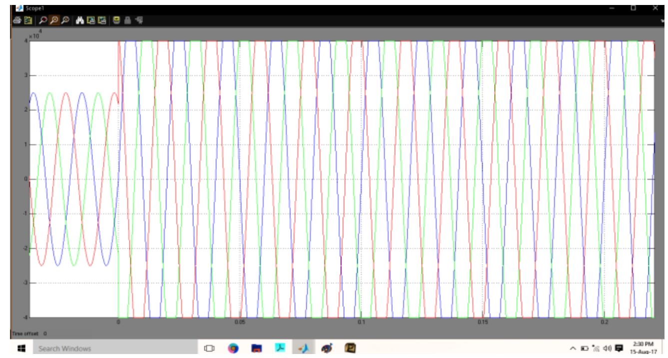

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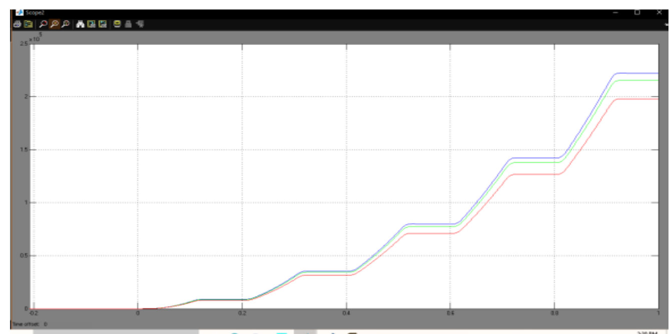
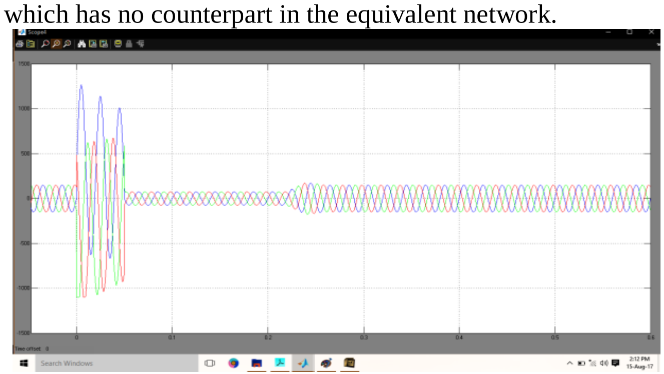


(c)

Fig.10. 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.

This is due to the differences in the line current and the capacitor voltages, in the two aforementioned cases, after breaker CB41 in the nine-bus system is tripped at 50 ms, which has no counterpart in the equivalent network.



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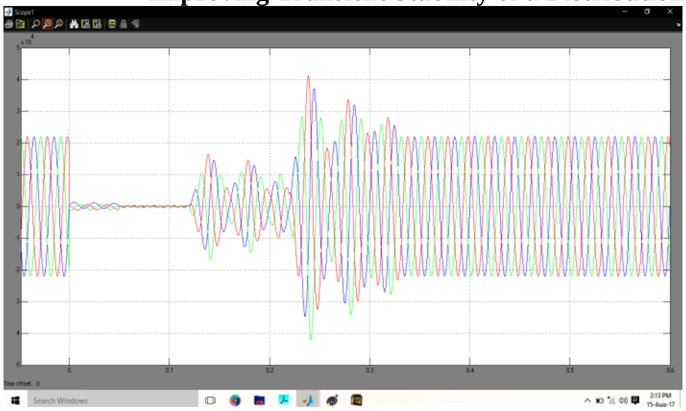
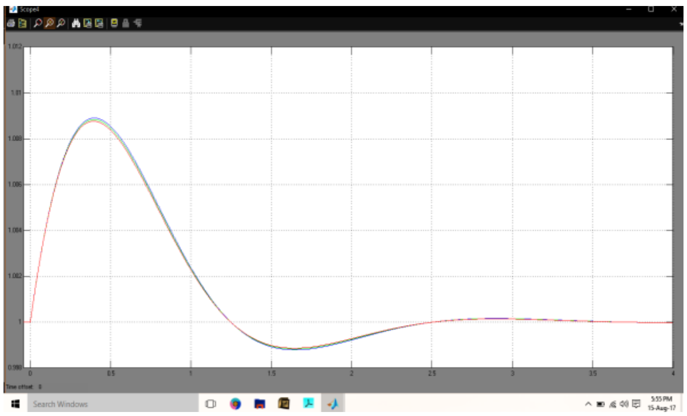


Fig:1(b)

Fig.11. Responses of the nine-bus system subsequent to the strike of fault FltA (a) Line currents.(b) Capacitor voltages.



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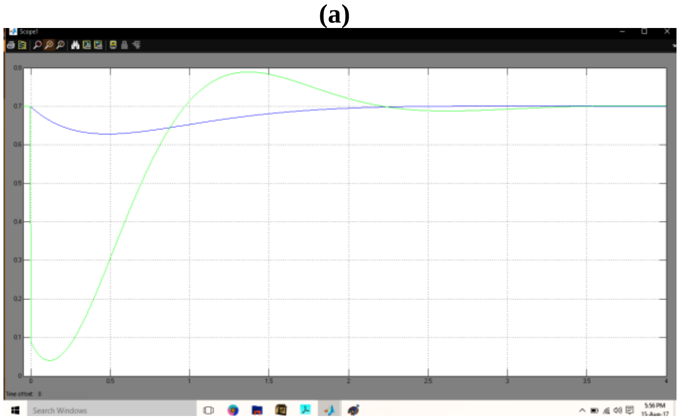

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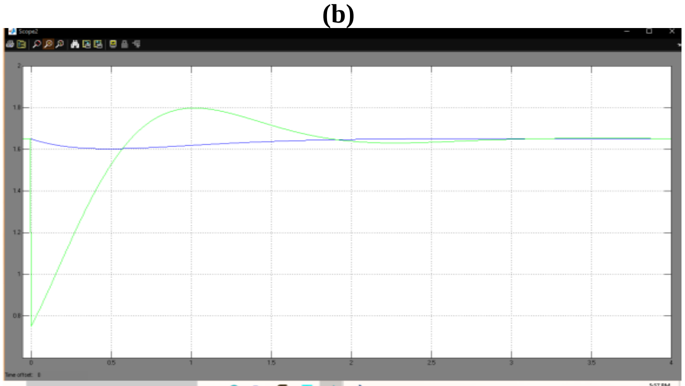

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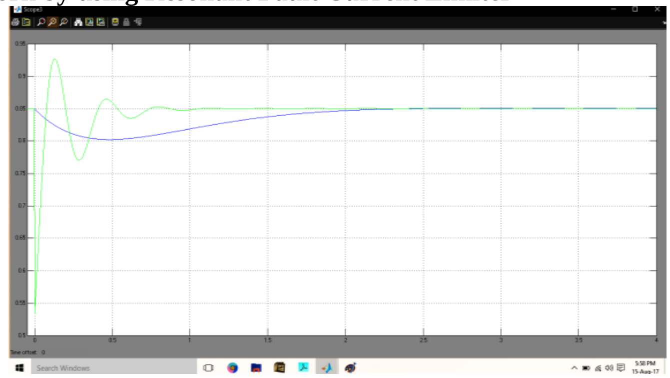

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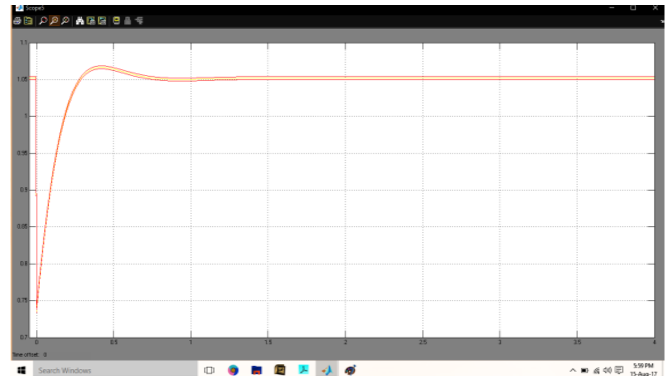

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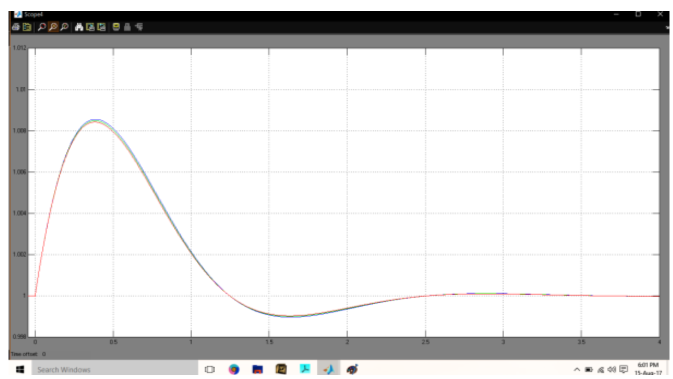
Fig.12. Responses of the nine-bus system without RFCL in line L45. (a) Generators rotor speeds. (b)–(d) Electrical and mechanical powers of the generators. (e) Generators terminal voltages.



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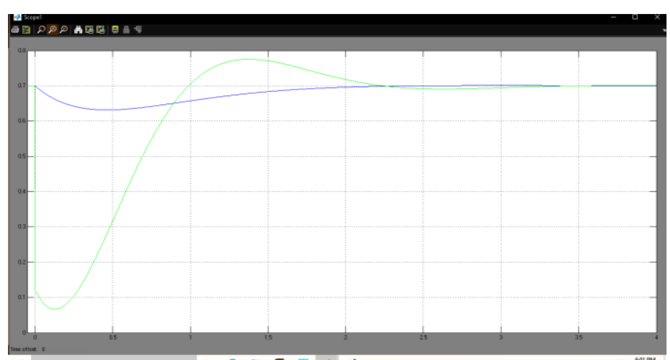

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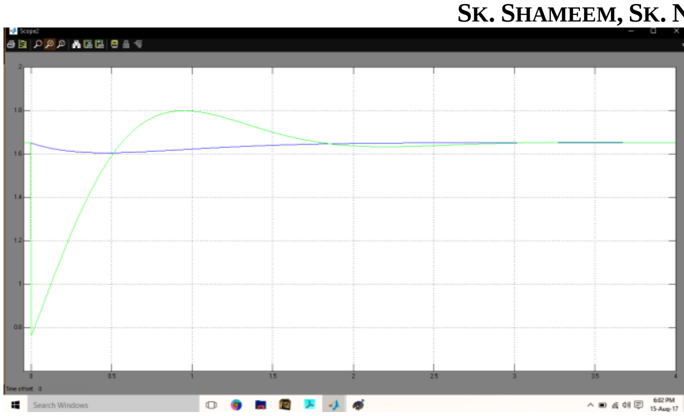

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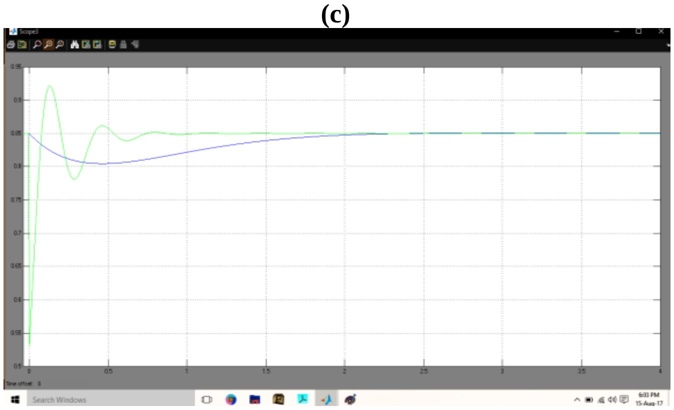

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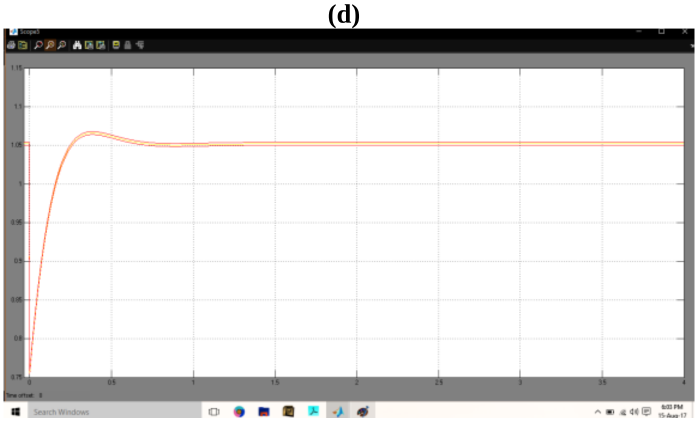

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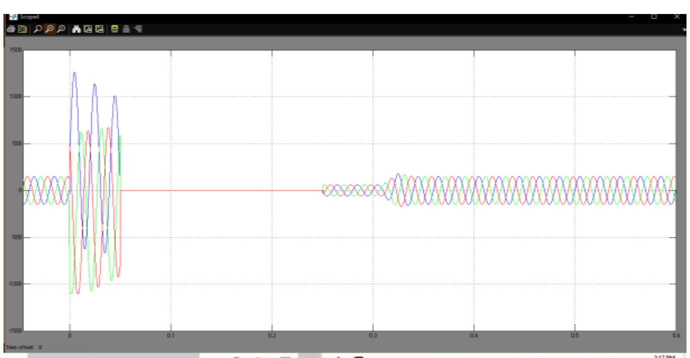
Fig.13. Responses of the nine-bus system with RFCL in line L45. (a) Generators rotor speeds. (b)–(d) Electrical and mechanical powers of the generators. (e) Generators terminal voltages.



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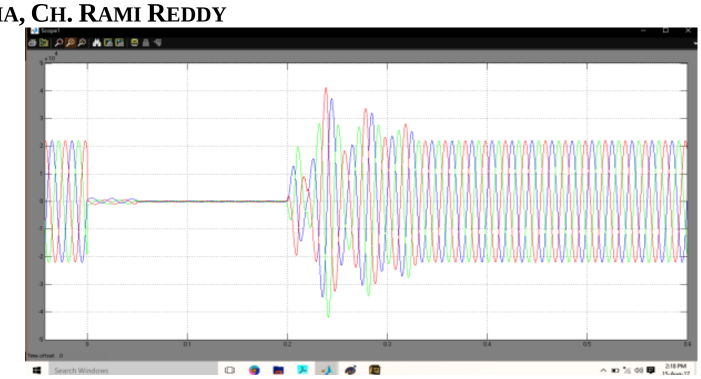

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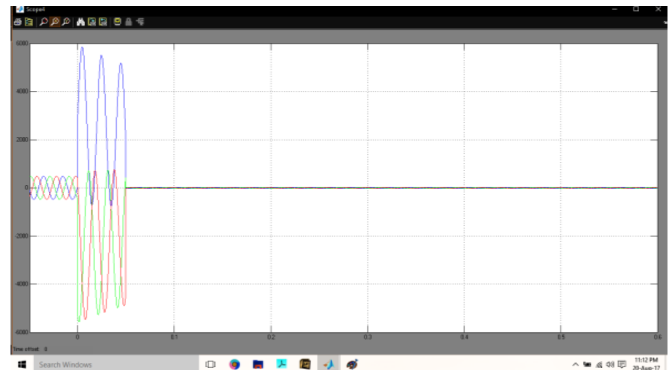
Fig.14. Responses of the nine-bus system subsequent to the strike of fault FltB (a) Line currents. (b) Capacitor voltages.



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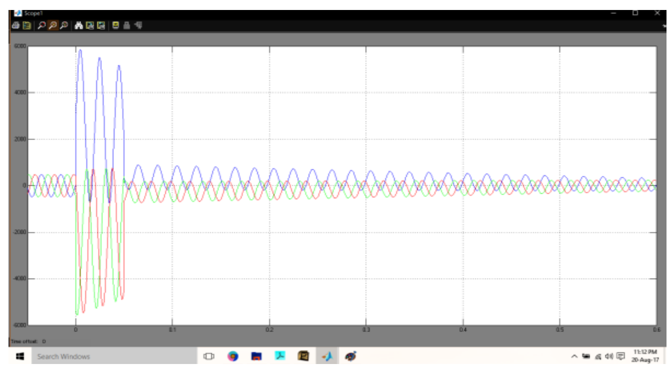

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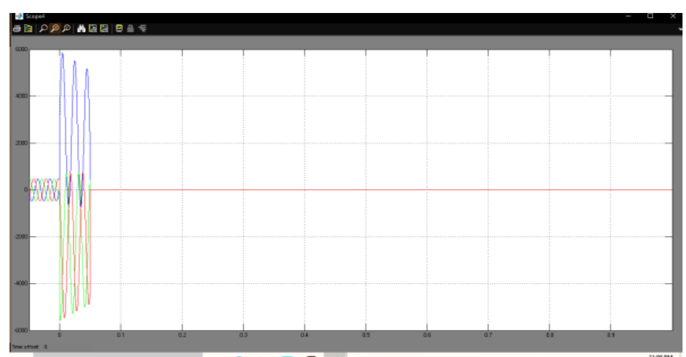
Fig.15. Instantaneous currents through lines L1 and L2 with (a) and (b) fixed Reactors.



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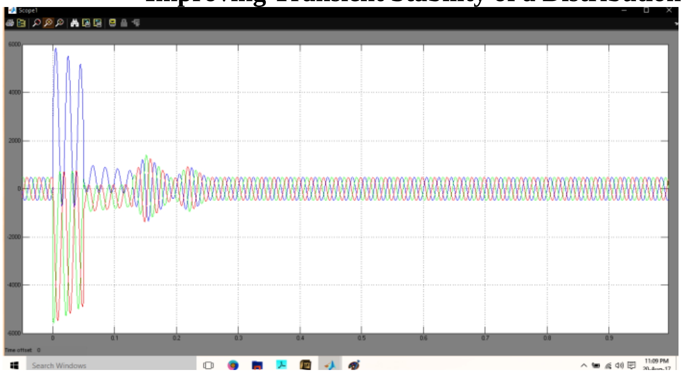

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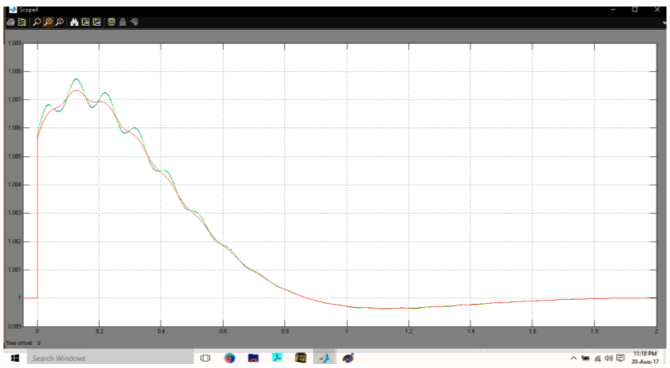
Fig.16. Instantaneous currents through lines L1 and L2 with (a) and (b) RFCLs.



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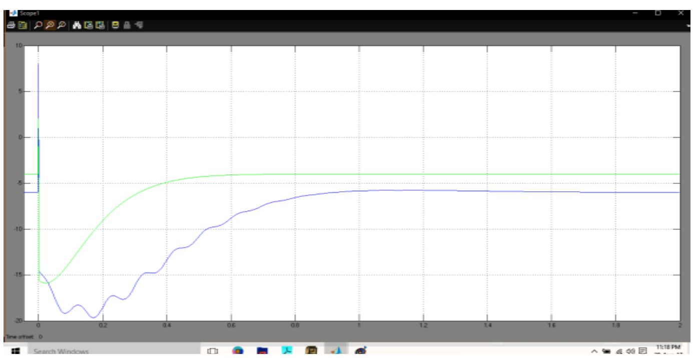

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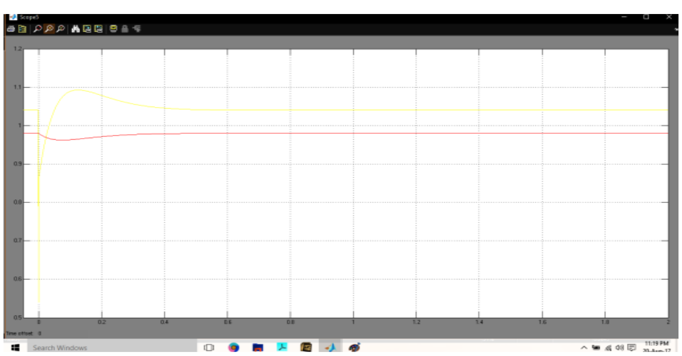

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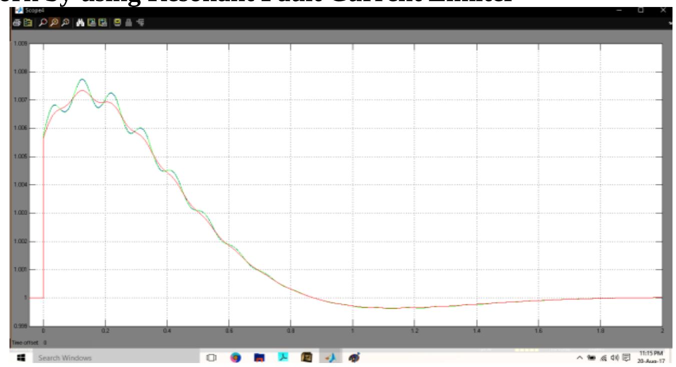
Fig.17. Responses of the reduced network with fixed reactors to a 3LG fault in line L1. (a) Rotor speeds, (b) rotor angles with respect to G3, and (c) terminal voltages of generators.



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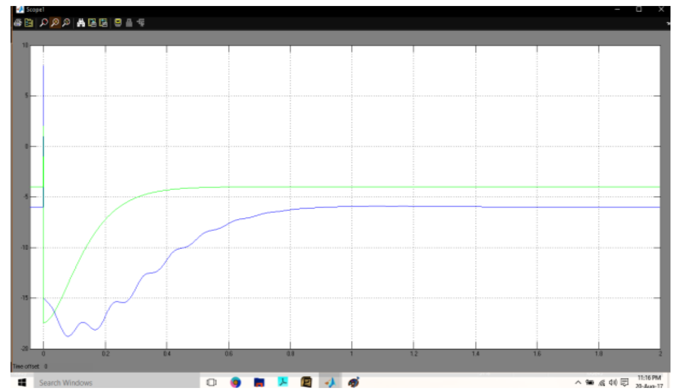

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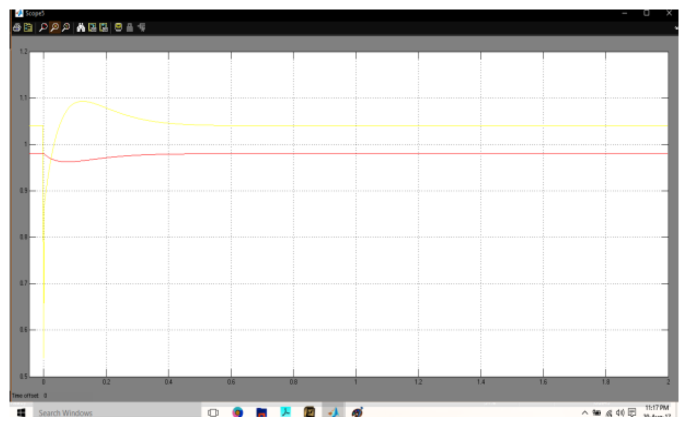

(c)

Fig.18. 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.

IV. CONCLUSION

This project 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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