Comparative Performance of Frequency Response Analysis and IEEE Std. C.37 in Transient Recovery Voltage Analysis of a Circuit Breaker with Fault Current Limiter (FCL)

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Abstract: One of the main problems in high voltage power stations is increasing the short circuit level. It causes some problems for circuit breakers and other station equipments. Using the series reactors is one of the methods for reduction and control of the short circuit level. This paper investigates the effects of the series reactor installation and the requirements of the circuit breaker on the CB interruption capability. The case study is a real power system in which the FCL installation analysis is carried out. The IEEE C.37 Standard is used for the selection of the size and the location of the high voltage capacitors. EMTP-RV software has been used for the analysis of the suggesting scenarios and frequency response of the suggested topologies.
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1. Introduction

One of the methods to reduce the short circuit currents in the power system is using the Fault Current Limiters (FCL). After optimum selection of the size and the location of the FCL, some studies must be carried out to determine the FCL effects on the CB performance. In fact, the addition of a FCL may affect the power network topology (Li, et al., 2008).

Circuit breakers are the most important equipments in high voltage power stations. Optimum selection of CBs and their requirements have vital role to control their Transient Recovery Voltage (TRV). Important parameters of the CB are speed, precision and capability to interrupt the fault current.

Two key characteristics of the CB are Transient Recovery Voltage (TRV) and the Rate of Rise of Recovery Voltage (RRRV) characteristics. If the Transient peak voltage and oscillation frequency on the CB contacts are beyond the CB capabilities, it may cause the failure in the fault current extinguish. Transient peak voltage and the oscillation frequency are depending on the power network topology. They could vary with the installation of some devices such as capacitor, rector and cables (Martinez, et al., 2005).

With the growth of the power system and the electric loads, the generation capability should be increased. So, the power transmission should be developed. The power transmission network needs some new studies and some changes in the power system topology such as the expansion of the present power stations, the installation of some new transmission lines, double circuiting of some of the present transmission lines and using FACTS devices.

2. Material and Methods

The growth of the power system always increases the short circuit level and would close the system to the instability margin. The present network design should respond to the present and future requirements of the power system planning. The economic objectives should also be considered. The growth of the transmission and sub-transmission network and the increasing of the short circuit level would make some serious problems in the power system operation. So, the short circuit level would be higher than the present CB interruption capability in some of the high voltage power stations. This causes a delay in fault clearing and so endangers the power system stability and failure of some of the power station equipment. Two forthcoming methods are changing of the present equipments with equipments with higher short circuit interruption capability and using an appropriate method for control and reduction of the short circuit level (Ye et al., 2002). In view of the technical and economical considerations, excepting some special applications, the second technique has a higher priority.

The EDF Company has some considerable simulation and experimental researches to study the TRV and RRRV resulted from the series reactor fault current limiter usage (Shoup et al., 2005). They have acquired some valuable results. Some similar studies have been carried out in Hydro-Quebec and B. C. Hydro states of Canada on the medium voltage feeders in which some series fault current limiter have been used (Peelo et al., 1996). Some successful experiences in using of these FCLs have been reported for 362 and 550 kV power systems in Brazil (Amon et al., 2005) some experiences have been studied and simulated for a 138 kV power station in USA (Castanheira, 2004). The application of this fault current limiters and compensating some related problems has been reported (Peelo et al., 1996) for 345 kV high voltage circuit breakers. Regarding to the static security constrains, firstly the size of the series reactor is determined based on the IEEE C.37 Standard. Then, the effect of this installed series reactor on the transient stability of the generators is studied. The supplementary equipments are acting as a filter, so the frequency response in any part of the power system should be evaluated. Then, according to the series reactor installation, the frequency response of the transient recovery voltage generated on the circuit breaker contacts when a fault is cleared is studied. Finally some appropriate strategies are proposed to reduce the generated transient over voltages. Any change in the network requires a comprehensive study of Technical and economics. Due to the continuing importance of energy and the influence of any change in the power network, the power system is very conservative to any changes in the topology of power network. So, the power system is always is opposed to any change in the existing arrangement in the power network. However, this issue may cause some terrible events in the power system (Park et al., 2007).

Different standards for such conditions are presented, but the offered suggestions for each network may not be acceptable for all cases. Thus, for using the advantages of these proposals, the over size design also is carried out. Several incidents of explosion of CBs in power transmission networks and sub-transmission have been reported in Iran (Khodabakhchian et al., 2006). The most usual reason of these explosions has been the disability of the CBs in the extinction of the fault current-generally due to network topology changes and increased levels of short circuits of the main power stations or the adjacent power stations.

IEEE C.37 standard evaluates the capability of the CBs for fault current extinction on the base of the $1-\cos\omega t$ envelope curve. Accordingly, it is possible to determine statically for how much fault current the CB has the interruption capability and in what conditions it may not have a desirable operation. Regarding the supplementary equipments for each CB such as reactors and capacitors, any CB has implicitly a TRV interruption capability curve. The, $\omega = 2\pi f$ frequency in the $1-\cos\omega t$ envelope curve is determined by this standard for each CB and for every conditions. In this Standard, the conditions have been considered as static. This means that the power frequency has been disregarded against the TRV oscillation frequency. For example, the Figure.1 shows the differences between the power frequency and the TRV oscillations frequency.

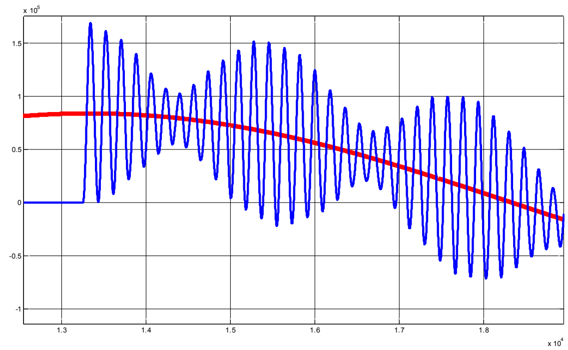


Figure 1. Power frequency (dot) versus the TRV oscillations frequency (solid)

The investigation showed that TRV control measures needed to be taken. Details of these control measures, including the development of dedicated capacitive equipments to apply across the series reactor, are described. The purpose of series reactors is to limit the magnitude of fault current. The reactors can be applied in a number of locations in order to achieve this purpose, on main buses, on feeders or in transformer neutrals. The following are the specific objectives of this paper on transient recovery voltage requirements associated with the application of current-limiting series reactors:

- Determine the TRV requirements associated with protective line circuit breakers for representative switching stations for the system under study for faults located just beyond the series reactor on the line-side.
- Specify the capacitance needed, and placement of capacitance, to control the TRV to within acceptable limits, as necessary, from the frequency response point of view.

According to the standard IEEE Std. C37.011-(1994), TRV CB curves for 121kV voltage levels and above is as following:

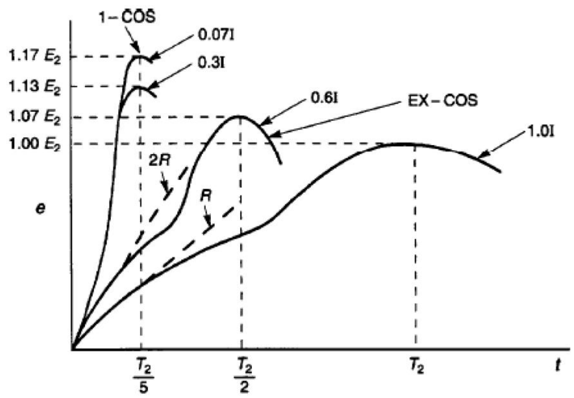


Figure 2. CB curves for 121kV voltage levels and above

Regarding the Figure.2, the TRV envelope curve for the nominal fault current is an exponential-cosine curve. In this Figure, in addition to the TRV envelope curve for the nominal fault current, the TRV curves for 60%, 30% and 70% of the nominal fault current have been shown. According to this Figure, for 30% of the nominal fault current and lower, the curve has been turned from the exponential-cosine form to the exponential form. Considering the above explanations, the TRV envelope curve will be an exponential form Figure.3.

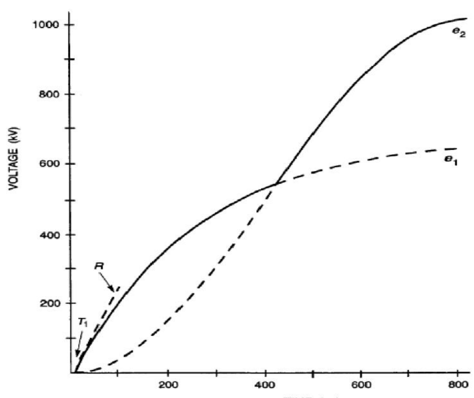


Figure 3. TRV envelope curve

According to this standard and the nominal fault current, the mathematical equation describing the exponential curve is as following:

$$e_1 = E_1(1-\varepsilon^{-t/T}) \quad (1)$$

$$e_2 = \frac{E_2}{2}(1-\cos(\frac{\pi t}{2})) \quad (2)$$

The CBs for rated 132 KV voltage should be able to tolerate the rated over voltages as (139 = 132 * 1.05) kV. So due to the standard, a 145 kV is selected.

Based on the ANSI C.37.06 (1987) for rated current and maximum voltage (E_{max}=145kV):

$$E_2 = 1.76E_{\max} = 1.76*145 = 255 \quad (3)$$

And:

$$T = 310\mu s \quad (4)$$

3. Case Study and Simulation Results

In order to complete the study, the time and frequency domain simulation in a real system are performed. This system had four local units and 4 units from adjacent area. In the development plan 2 steam units are added to system. Combined Cycle Gas Turbine Development Plan (Porkar, Abedi, 2009)

This system is connected by double lines to network. In this study the performance of these two lines are studied. Single line diagram of power station is shown in Figure.4 and the fault location is specified. From point of view time and frequency domain simulation, the capacitance and reactance of each section should be determined.

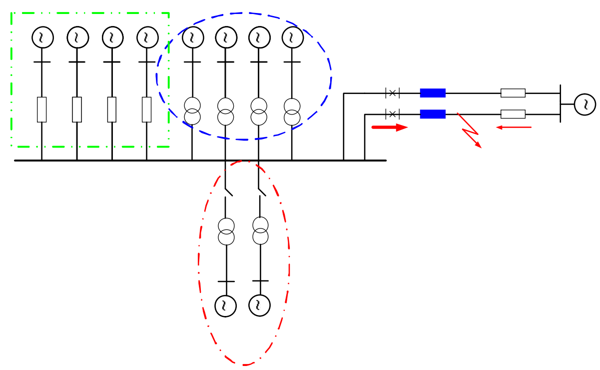


Figure 4. Single line diagram of power station

For 200 MVA unit transformers (for each phase of 66.66 MVA) values, CL, CH and CHL, respectively are 9000, 3000 and 12000 pF. Also the transformer reactance for short circuit impedance of 11% is equal to:

$$(132^2/200)(0.11)=9.6 \quad (5)$$

Short-circuit before the reactor and the currents flowing through the CB in the worst case is shown in Figure 5.

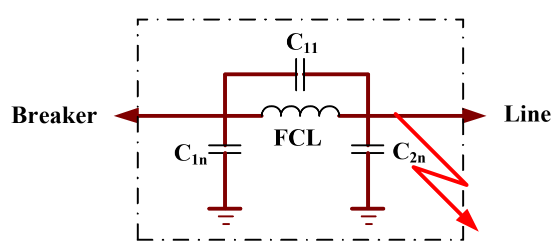


Figure 5. Fault current Limiter and TRV requirements

The generators transient modeling for the studied time period is not important and in this case study not considered. Due to the table B.8 of the standard IEEE Std. C37.011 (2005), the stray Capacitor value of the reactor is selected as 200 pF, and according to the table B.6 of this standard, the stray capacitor of the CBs and the bus sections of the GIS power stations are considered as 80pF. According to the table B.3 of this standard, the stray capacitor of the PTs is considered as 300pF. Finally, the stray capacitor of the CT's inside the GIS power stations is considered as 100pF.

According to the single line diagram of the power station concentrating on the line, two PTs and 4 CTs should be modeled. The CTs are located between the CBs and the reactor, but PTs are after the reactors. Due to 60m of total length of the GIS bus-bars and assuming the 70pF per unit capacitor, the bus-bar capacitor is considered as 4200 pF.

Standard IEEE C.37 has determined the capacity of each capacitor of the above capacitors. For the stating, these capacitor values have been used for the simulation. In the next step, the CB's response against the faults should be to determine and the interruption capability of the CB's should be studied. So it is necessary to obtain the interruption capability curves of the CBs in the new state and then with comparing the voltages across the CB. Finally the interruption capability of the CBs is compared with the standard interruption capability. If the interruption CBs curves were lower than the System TRV voltage, the CB would have some difficulty in the interruption. Figure 6 shows the CB interruption capability curve and the TRV for the case in which the C11=9nF. Dotted curve related to the CB capability of the interruption (the $1-\cos\omega t$ curve) and the continuous curve shows the CB TRV curve. By choosing this capacitor, in accordance with the proposed standard IEEE C.37, it is clear that the CB has difficulty in the interruption. The interruption capability curve (dotted) and the CB TRV curve (continuous curve), for parallel capacitance of 9nf, based on IEEE C.37 standard, in this case the CB will not have the desired operation.

Now assume that a 12nF capacitor is selected instead of the previous one. Again the above mentioned curves are shown in the Figure 7. In this case the CB will have a desired operation.

Accordingly, for capacitors between phases and the ground, similar studies are carried out. The suggested capacitor in the Standard is 12nF, but In this case, the higher capacitors should be selected to ensure a desired performance. In this case the minimum capacitor needed is 16nF.

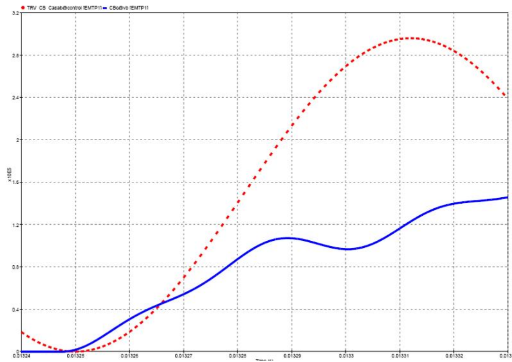


Figure 6. TRV (solid) and Capability Curve (dotted), C11=9nF

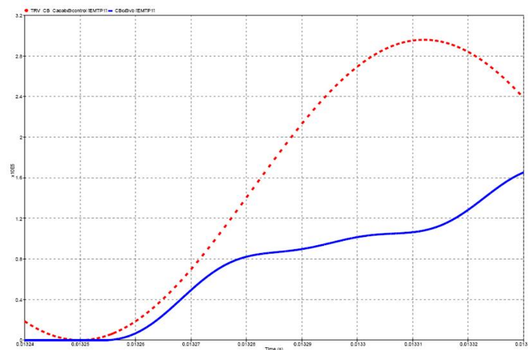
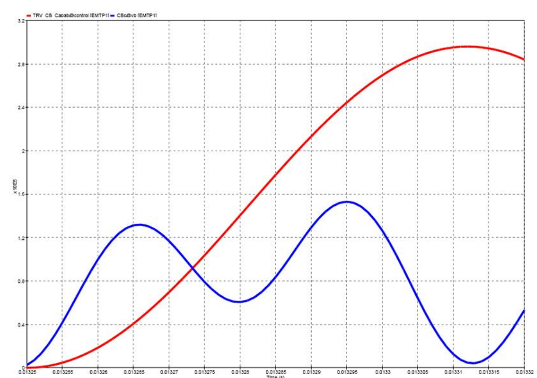
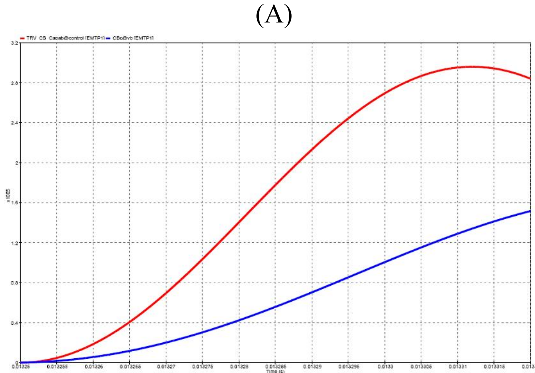


Figure 7. TRV (solid) and Capability Curve (dotted), C11=12nF



(A)



(B)

Figure 8. TRV (solid) and Capability Curve (dotted), (A), C1n= C2n= 12nF; (B), C1n= C2n= 16nF

Since each of these equipment is added to the system are operating as a filter in the power system, firstly the frequency response of these filters should be determined.

Because the frequency of power line carrier systems is about several kHz signal and should not attenuate or filter the communications signals of the power network. On the other hand, the same frequency response could be used to evaluate the system response for topological changes. For this purpose, for each change in the system including the capacitor changing or changing of the location of the capacitors in the circuit, the frequency response is presented in Table 1 and plotted in the Figures 9-12.

Table 1. Dominate frequencies of configurations

	With Fault		Without Fault	
	f1	f2	f1	f2
Without any apparatus	6145	9085	5425	8625
only parallel capacitor with FCL	4800	7940	5005	9350
only capacitor between phase and ground	5070	8045	4060	7870
all capacitor	3040	7770	3195	7800

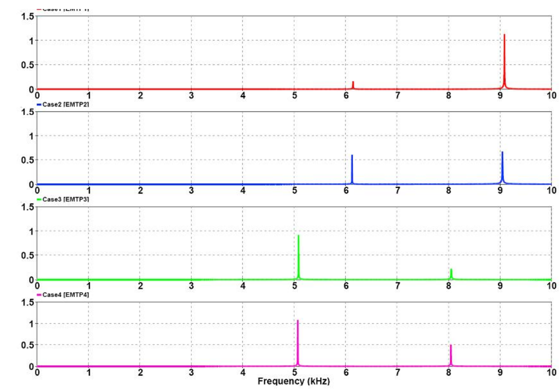


Figure 10. Frequency response by increasing the capacitance of C1n

4. Discussions

In this paper effects of the series reactor installation and the requirements of the circuit breaker on the CB interruption capability were considered. At first step the proposed configuration and capacitance selection based on IEEE C.37 standard simulated in time domain were carried out. The results showed that the capability interruption curve by choosing proposed values can't maintain the static security of CB's and may be threat the CB's desire operation.

Then, calculated $1-\cos\omega$ frequency curve and frequency response of the system under normal and faulty conditions are simulated.

The results show that if the system frequency response with dominant frequencies (f1, f2) higher than the $f = \omega/2\pi$ CB's desire operation is not guaranteed.

Behavior of the system trend in frequency response also shows that the change in capacitor between phase and ground with a high speed of the dominant frequencies transferring to the left. Therefore, by selecting the optimum and economic capacitors the performance of CB's will be improved.

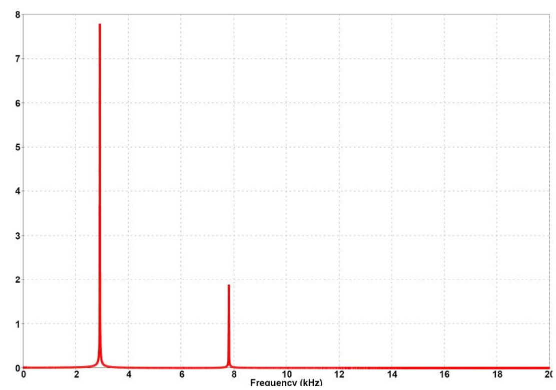


Figure 11. Frequency response for C11=12nF and C1n=16nF, Case: without fault

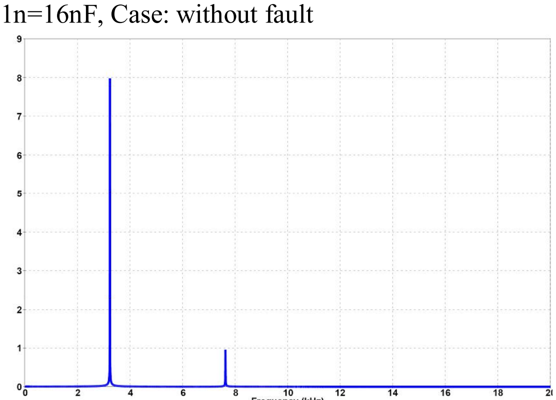


Figure 12. Frequency response for C11=12nF and C1n=16nF, Case: with fault

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