

Techno-Economic Study of Series Current Limiting Reactor and Its Impact in the 11KV Network with Harmonic Pollution

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Abstract
Survey & selection of oil filled fault current limiting series reactor for limiting short circuit fault currents from 40KA to 22KA at 11KV level in an existing distribution substation due to change of source substation. The impact of source X/R ratio variation, maximum & minimum short circuit currents on the acceleration times of the 11KV motors and variance in voltage regulation due to change(s) in the conventional Series reactor impedance is studied. Impact of power factor improvement capacitors on the short circuit level and on series reactor impedance is assessed. Expected harmonic pollution due to VSD's is estimated and its influence on the series reactor impedances is assessed for resonant conditions. Transient Recovery Voltage and Rate of Rise of Recovery Voltage are studied for verification of circuit breakers' ability to isolate the fault conditions. Techno - economic evaluation of series reactor(s) impedance(s) for cost effectiveness along with the ability of reputed international testing houses for testing is assessed. The study results reflect that the constraints of test laboratories to test the specified series reactors will have an impact on the selection of series reactor impedance. While higher impedance selection will be useful from the short circuit point of view, it will pose difficulties with reference to physical dimensions of the equipment, cost and other related issues.
Keywords: Current Limiting Reactor (CLR), Short Circuit Current, Harmonics, Cost

Introduction:

Ever increasing demand of electrical power [1], [2] necessitates increased power generation which in turn causes increased short circuit current at switchboards and equipment. Also network restructuring and modifications would pose issues related to short circuit capability of existing switchboards. Increased short circuit currents can cause severe mechanical and thermal stresses leading to damage of the equipment and operating facility. Many a times, it is not possible to replace the existing switchboards with higher rated short circuit capability due to production considerations and cost reasons. When the options of dividing the bus bars and/or splitting the network cannot be implemented due to reasons of reliability and security of power, and application of patented current limiters would pose issues related to installation & space constraints in the existing switchboards and substations, then the series current limiting reactor is an acceptable solution for limiting the short circuit currents. [1],[2].

This paper intends to present the various techno-economic aspects involved in the selection of series current limiting reactor and its application for limiting fault current from 11KV, 40KA at the source end substation to a level of 11KV, 25KA at the receiving end substation.

Various types of series current limiting reactors are available in the market. It is noted that a revival of interest in the application of current limiting reactors coupled with solid state electronics schemes and superconductivity are in the various stages of development. Few of the applications appear to be successful in USA electrical networks. It is felt that for 11KV network distribution of a hydrocarbon industry, taking into consideration cost, familiarity and hands on aspects, the conventional type of series current limiting reactors are adequate for the subject application.

1. Brief Description of the electrical network:

Substation 'X' is rated for 72MW at 11KV and feeds to Substation 'Y' and Substation 'Z'.

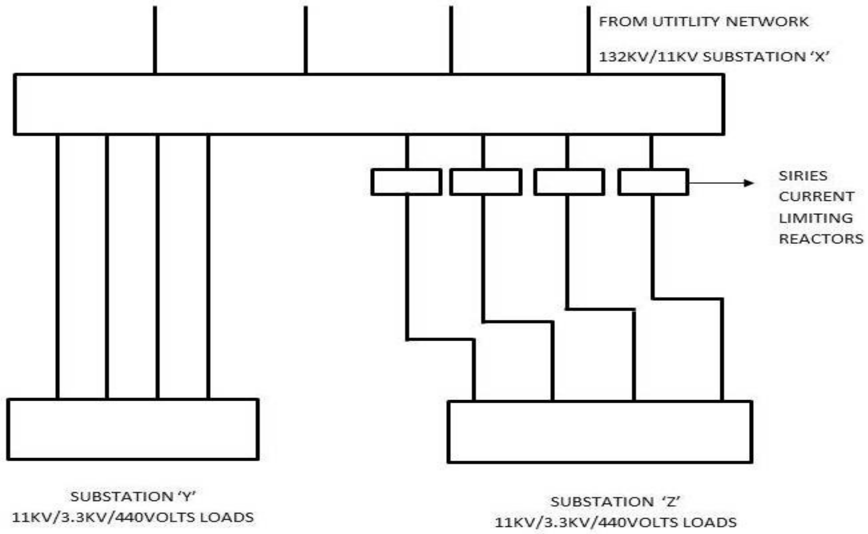

Figure1.

Type and Nature of the connected load: Total maximum demand of Substation 'Y' is 55MW. Non-linear loads to the extent of 36MW operate on Substation 'Y' 11KV bus. Substation 'Z' has maximum demand of 12MW consisting of motors and power factor improvement capacitors at 11KV level.

The other load composition consists of induction motors of various sizes connected to 3.3KV and 440 volt level along with associated transformers. Lighting loads and small nonlinear loads such as battery chargers, UPS systems, Computers and Switch Mode Power Supplies (SMPS) are connected at the 440 volts level.

Presence of Harmonics and Harmonic related information:

As the nonlinear loads operate at Substation 'Y' 11KV, harmonic pollution is present in the network. The main contribution of harmonics is from 11KV Variable speed drives. The Variable speed drives are of voltage source type with high pulse rectifiers.

The capacity of UPS systems & Battery Charger(s) is much less than 15% of the corresponding transformer capacity at the 440 volt level hence the harmonic presence is ignored.

2. Reactor Related Preliminary Aspects:

Type of Reactor: It is noted that application of air core, dry type reactors are more common in major electrical networks for the current limiting purposes. However taking into the consideration the existing practice and presence of traces of Hydrogen sulphide, outdoor type, three phase, air core, oil immersed, magnetically shielded series current limiting reactors are considered for the subject application and techno economic evaluation.

Reactor location: Based on the constraints of space availability and extent of modification required at Substation 'Z', it is considered that installation of reactors will be part of the Substation 'X'. Further installation of reactors at source end (optimum location for the reactors) has the advantage of reducing short circuit current on the linking cables from Substation 'X' to Substation 'Z'.

Manufacturer's availability: It appeared from the survey that more number of manufacturers are available for dry type air core reactors. However few manufacturers are also interested in the manufacture of air core, oil filled type reactors.

3. ETAP system Studies:

Size of the Reactor: For the purpose of limiting fault current which is at the level of 40KA at Substation 'X' to the level of 25KA at Substation 'Z' two reactor values 0.3 ohms and 0.5 ohms are considered. For each of the value of the reactor four varieties of system studies are conducted. They are namely

Load flow study

Short Circuit study

Motor starting capability study

Harmonic Assessment study.

Load Flow Study: Initially Substation 'Z' was fed from the Substation 'W' (not indicated in the Figure 1). During the process of network reorganization, Substation 'Z' is proposed to be fed from Substation 'X'. Introducing Series Current Limiting Reactors in the electrical network would increase the impedance of the network and other networks parameters have also changed due to the network modifications, Load Flow study is carried out for the verification of required power flow and voltage regulation aspects. From the ETAP Load Flow studies, it is noted that the voltage regulation and power flow related aspects are within the acceptable range for both 0.3 and 0.5 ohm reactors [3], [4].

Short Circuit Study: Before the network modification, the short circuit level at Substation 'Z' was 17.0KA (Ik) as against switchboard rating of 25KA. At the new source substation (Substation 'X'), the calculated fault level is in the range of 27KA (Ik) from utility without considering fault contribution from the downstream and switchboard is rated for 40KA. To ensure that the Substation 'Z' fault level does not increase to 22KA, system studies are carried out for both 0.3ohm and 0.5ohm Series Current Limiting Reactor values. It is to be noted that the presence of capacitor banks at Substation 'C' will not alter the peak short circuit current (Ik") at the 11KV bus and hence ignored.

X/R ratio and its impact: It is known that utility undertaking fault levels are increasing and system impedances values are expected to change due to power increase and expansion of network at the utility end. Although it is not possible to assess how much increase in the short circuit current will be available in future and how much variation will be there in the X/R ratio, a few calculations were carried out by varying the X/R ratio and source short circuit currents and its impact on the load flow and short circuit currents at the Substations. The ETAP results are mentioned hereunder in Table 1, 2, 3, 4 and 5. The below projected current values are based on the three phase fault simulations.

Table 1

Impedance value of CLR = 0.3 ohm

	Substation Name	Source X/R = 4.61		Source X/R = 6		Source X/R = 18		Source X/R = 30	
		Voltage (%)	Voltage (KV)	Voltage (%)	Voltage (KV)	Voltage (%)	Voltage (KV)	Voltage (%)	Voltage (KV)
1	Substation X	99.5	10.945	99.5	10.945	99.5	10.945	99.5	10.945
2	Substation Y	98.98	10.888	98.98	10.888	98.98	10.888	98.98	10.888
3	Substation Z	98.96	10.885	98.96	10.885	98.96	10.885	98.96	10.885

Table 2

Impedance value of CLR = 0.5 ohm

	Substation Name	Source X/R = 4.61		Source X/R = 6		Source X/R = 18		Source X/R = 30	
		Voltage (%)	Voltage (KV)	Voltage (%)	Voltage (KV)	Voltage (%)	Voltage (KV)	Voltage (%)	Voltage (KV)
1	Substation X	99.48	10.943	99.48	10.943	99.48	10.943	99.48	10.943
2	Substation Y	98.96	10.886	98.96	10.886	98.96	10.886	98.96	10.886
3	Substation Z	98.77	10.865	98.77	10.865	98.77	10.865	98.77	10.865

Table 3

Impedance value of CLR = 0.3 ohm; Source Fault Level (max) =2789 MVA at 132KV level

	Substation Name	Source X/R = 4.61			Source X/R = 6			Source X/R = 18			Source X/R = 30		
		Ik" (KA)	Ip (KA)	Ik (KA)	Ik" (KA)	Ip (KA)	Ik (KA)	Ik" (KA)	Ip (KA)	Ik (KA)	Ik" (KA)	Ip (KA)	Ik (KA)
1	Substation X	32.524	81.824	26.331	32.483	82.574	26.298	32.424	84.435	26.258	32.417	84.839	26.256
2	Substation Y	30.332	74.032	24.556	30.302	74.648	24.532	30.265	76.173	24.51	30.262	76.503	24.511
3	Substation Z	24.108	58.027	19.237	24.092	58.382	19.224	24.074	59.257	19.217	24.073	59.446	19.218

Table 4

		Impedance value of CLR = 0.5 ohm ; Source Fault Level(max) = 2789 MVA at 132KV level											
Substation Name		Source X/R = 4.61			Source X/R = 6			Source X/R = 18			Source X/R = 30		
		Ik" (KA)	Ip (KA)	Ik (KA)	Ik" (KA)	Ip (KA)	Ik (KA)	Ik" (KA)	Ip (KA)	Ik (KA)	Ik" (KA)	Ip (KA)	Ik (KA)
1	Substation X	32.459	81.703	26.331	32.418	82.454	26.298	32.359	84.317	26.258	32.353	84.721	26.256
2	Substation Y	30.277	73.936	24.556	30.247	74.552	24.532	30.21	76.078	24.51	30.208	76.409	24.511
3	Substation Z	21.54	52.44	17.018	21.526	52.718	17.007	21.509	53.401	16.999	21.508	53.548	17

Table 5

	Source X/R = 4.61			Source X/R = 6			Source X/R = 18			Source X/R = 30		
	Ik" (KA)	Ip (KA)	Ik (KA)	Ik" (KA)	Ip (KA)	Ik (KA)	Ik" (KA)	Ip (KA)	Ik (KA)	Ik" (KA)	Ip (KA)	Ik (KA)
	Impedance value of CLR = 0.3 ohm, Source Fault level = 5000 MVA at 132KV level											
Substation Z	25.319	61.514	20.532	25.309	61.743	20.523	25.297	62.303	20.518	25.297	62.423	20.519
	Impedance value of CLR = 0.3 ohm, Source Fault level = 7500 MVA at 132KV level											
Substation Z	25.879	*63.15*	21.129	25.871	*63.312*	21.123	25.863	63.709	21.119	25.863	*63.794*	21.120
	Impedance value of CLR = 0.5 ohm, Source Fault level = 5000 MVA at 132KV level											
Substation Z	22.462	55.175	18.022	22.453	55.350	18.015	22.442	55.781	18.009	22.442	55.874	18.010
	Impedance value of CLR = 0.5 ohm, Source Fault level = 7500 MVA at 132KV level											
Substation Z	22.883	56.442	18.480	22.877	56.566	18.475	22.869	56.869	18.471	22.869	56.934	18.472

Motor Starting Capability: Substation 'Z' has approximately 3500KW rated motors in multiple numbers that operate at 11KV level in Direct On Line Mode. Studies were carried out for motor starting capability for both the values of Current Limiting Reactors (CLRs) when the line voltage at Substation 'Z' falls down to 80% which represents worst operating condition. Introduction of CLR did not change the motor starting times much at Substation 'Z'. The results are mentioned hereunder in Table 6.

Table 6

Substation C Motor Starting Time (in seconds) at Source Fault Level(minimum) = 1852 MVA at 132KV level			
Impedance value of CLR = 0.3 ohm		Impedance value of CLR = 0.5 ohm	
Source X/R = 6.04	Source X/R =12	Source X/R = 6.04	Source X/R = 12
Time for Motor Starting in seconds	Time for Motor Starting in seconds	Time for Motor Starting in seconds	Time for Motor Starting in seconds
4.2	4.2	4.2	4.2

Power Factor: The voltage drop at the reactor is a function of the power factor. It is mandatory to maintain 0.95 power factor at Substation 'X' 11KV bus bar. Substation 'Z' has two numbers capacitor banks each of size 1800 KVAr operating on 11KV bus. The VSD's at Substation 'Y' are intended to be operated at high power factor in the range of 0.95 to 0.97 during their continuous operation. The ETAP studies indicates power factor at 11KV buses of various substations as indicated in the Table 7.

Table 7

Substation	Impedance value of CLR = 0.3 ohm			Impedance value of CLR = 0.5 ohm		
	3 Tr, 3 CLR	3 Tr, 4 CLR	4 Tr, 4 CLR	3 Tr, 3 CLR	3 Tr, 4 CLR	4 Tr, 4 CLR
Substation X	97.8	98	97.9	97.8	97.8	97.8
Substation Y	98.1	97.7	97.7	98.1	97.7	97.7
Substation Z	84.8	85.2	85.2	84.8	85.2	85.2

Harmonic Assessment Study: Substation 'Y' has considerable number of variable speed drives of 4MW rating. Harmonic Assessment study indicated the following results of Voltage and current Distortion with Current Limiting Reactors of 0.3ohm and 0.5ohm at 11KV levels of respective substations:

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Table 8

Substation Name	VTHD% for CLR 0.3 Ohm	VTHD% for CLR 0.5ohm
Substation X	0.97	0.99
Substation Y	0.99	1.03
Substation Z	1.22	1.1

Table 9

Substation Name	ITHD% for CLR 0.3 Ohm	ITHD% for CLR 0.5ohm
Substation X	xxx	xxx
Substation Y	xxx	xxx
Substation Z	xxx	xxx

From the evaluation of above system studies with both 0.3ohm and 0.5 ohm reactors, generally it appears that 0.3 ohm and 0.5 ohm reactors are acceptable for X/R ratio of 4.61 and Utility source fault level of 2789MVA at 132 KV level, at higher levels of source fault level, the Ip are marginally higher than the switchboard assigned ratings for 0.3 ohm rated reactors. Please refer Table 10 for comparison of results:

Table 10

Evaluation basis	0.3 ohm CLR	0.5 ohm CLR	Remarks
Load Flow Study for present value of X/R ratio 4.6 and Utility fault level at 2789 MVA	ETAP results are technically Acceptable	ETAP results are technically acceptable	Based on the results both CLR values are acceptable.
Load flow for variations of Utility X/R ratio variation	ETAP Results are technically acceptable	ETAP results are technically acceptable	X/R ratio variation is imaginary for the study purposes.
Short Circuit Study for present value of X/R ratio 4.6 and Utility fault level at 2789 MVA	ETAP Results are technically acceptable	ETAP results are technically acceptable	This study represents present situation where X/R ratio 4.6 and Fault level 2789 MVA is obtained from Utility
Short Circuit Study for variations of Utility X/R ratio and projected Utility fault level at 5000 MVA	ETAP Results are not technically acceptable	ETAP results are technically acceptable	With the imaginary values of X/R and short circuit values 0.3 ohm CLR is very close to the rated values and not technically acceptable. However 0.5 ohm CLR is acceptable
Short Circuit Study for variations of Utility X/R ratio and projected Utility fault level at 7500MVA	ETAP Results are not technically acceptable	ETAP results are technically acceptable	With the imaginary values of X/R and short circuit values 0.3 ohm CLR is not acceptable. However 0.5 ohm CLR is acceptable
Motor starting time study	ETAP Results are technically acceptable	ETAP results are technically acceptable	Both 0.3ohm and 0.5 ohm CLRs are acceptable. The results projected in the table 6 are based on X/R = 4.6 and source minimum fault level of 1852MVA.
Power factor	0.95 power factor can be maintained for various modes of network operation	0.95 power factor can be maintained for various modes network operation	Both 0.3 ohm and 0.5 ohm current limiting reactors acceptable for maintaining the power factor at substation X.
Harmonic Study	VTHD values are less than acceptable 5% limit.	VTHD values are less than acceptable 5% limit.	Both 0.3 ohm and 0.5 ohm current limit reactor values are technically acceptable.

If so, general conclusion will be why not to opt for 0.5 ohm CLR which will ensure lower short circuit current at Substation 'Z' 11KV switchboard. However, prior to conclusion of the reactor ohm value other Reactor's critical parameters need to be assessed.

4. Series Current Limiting Reactor's Critical Parameters:

For current limiting reactors, in general three phase short circuit is usually the basis for specifying various parameters [5]. In an electrical network, three currents are that dealt with. Ip (peak short circuit current), Ik" (initial symmetrical short circuit current) and Ik (steady state short circuit current). In numerical terms of kilo amps, Ip is greater than Ik" and Ik" is greater than Ik. In general the Ip & Ik" current that flows in the reactor are

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the parameters that would influence the design and selection of reactor. Ip current deals with mechanical bracing requirements of reactor whereas Ik" deals with maximum short circuit current that flows in the reactor. In general, as the substations are far from the generating stations, it is customary to take Ik" to Ik. However, where ever the value of Ik" is known it is recommended to use Ik" value instead of Ik value.

Reactor continuous current rating: Continuous flow of current that would flow under steady state operating conditions to deliver the Continuous power to Substation 'Z' is the minimum current rating of the Current Limiting Reactor.

Reactor short circuit current time rating: In any electrical network all power components are assigned standard time ratings based on the need to withstand short circuit currents. These standard ratings are generally for one (1) second or three (3) seconds for the High Tension switchboards. However for current limiting reactors a minimum of two (2) seconds time rating shall be the standard value in line with clause 8.4.3 of IEC 60076-6. In the present context in line with the current design practice, three (3) seconds time rating is assigned for current limiting reactors.

Reactor short circuit current rating: This is an important rating that is required to be specified by the designer. Electrical equipment has standard short circuit ratings. For example, relevant IEC standard assigns standard ratings for an 11KV switchboard 25KA, 31.5KA and 40KA etc. However for reactors there are no such standard ratings assigned by IEC standards. This rating is to be determined by the designer to suit to the electrical network requirements. Then the question arises as to what shall be basis for specifying such fault current rating.

In the subject study following three aspects is considered:

Reactor rating of 40KA for 3 seconds: As the reactors are physically close to the Substation 'X' which has 11KV switchboard with short circuit fault rating of 40KA (3seconds), is it required to assign CLR rating to be for 40KA for 3 seconds as the reactor primary terminals will see 40KA fault current ?

Reactor rating of 25KA for 3 seconds: As the reactor is limiting the fault current to 25KA at Substation 'Z', is it required to be rated for 25KA for 3 seconds?

Assigning a rating of 40KA for 3 seconds or 25KA 3 seconds would make the reactors bulky and costly.

Please see the Table 11 below which does not include any space and civil construction costs:

Table 11

Reactor value in Ohms	Assigned current rating	Approximate Physical dimensions of each reactor. L X W X H (all in meters)	Approximate Weight of the reactor	Indicative Budgetary Cost of each reactor
0.3	40KA/3seconds	2.5 X 2.5 X 4.6	12 tons	PRICE
0.5	40KA/3seconds	7.0 X 3.5 X 4.0	50 tons	3.125 x PRICE
0.5	25KA/3seconds	5.0 X 2.5 X4.0	27 tons	1.875 x PRICE

Reactor Testing & International Testing houses: The above cost figures are non-inclusive of reactor testing costs. It is important to note that short circuit test of current limiting reactors is a special test and will not be performed by the manufacturer unless specifically requested for. This test will prove the ability of the reactor to with-stand short circuit current for the specified time. On survey of testing houses it is noted that 0.3 ohms 40KA/3seconds reactors cannot be tested for full 40 KA for time period of 3 seconds due to the limitations of the test facilities at most of the reputed testing houses. Few of the testing houses declined to indicate the costs involved and few other testing houses suggested reduction of both time rating and short circuit current rating of the reactors for the purpose of testing of reactors. Although 0.5 ohm value Reactor can be tested but the cost involved is very high and is in the range of 60% to 70% of reactor cost. The cost and physical dimensions of the reactor depends on the ohm value, short circuit current & time rating of the reactor.

Fixation of the ohm value of the Reactor: Based on the above, it can be noted that specifying higher ohm value for a reactor is not only inappropriate and lead to other technical difficulties such as bigger foot print of the equipment, testing problems and higher cost etc. Furthermore, higher the reactor value, higher copper content would go into the reactor manufacture and hence the lesser the compliance to energy conservation principles as reactor dissipates heat.

From the above analysis it is appropriate to select 0.3 ohm value of series current limiting reactor for the subject application.

5. **IEC 60076-6 guide lines:** [5]

IEC standard 60076-6 clause 8.4.2 requires thermal short circuit current Iscr to be specified by the purchaser. Standard indicates two possible methods namely (a) Iscr shall not be less than the highest value of symmetrical r.m.s current under recognized fault conditions, which may be seen by reactor, (b) alternatively the rated thermal short circuit current may be derived from the specified system short circuit power, system voltage and reactor impedance.

(a) Reactor current rating to be based on maximum symmetrical r.m.s current as seen by any reactor under various operating conditions:

Based on the interpretation of (a) the recognized fault condition is either four reactors operating in parallel in normal operating condition or three reactors operating in parallel for abnormal operating conditions for delivery of 12 MW power to Substation 'Z'. However, it can be noticed that when one reactor is in service, the Ip, and Ik" are 34.0KA and 13.31KA respectively represent highest maximum currents through the reactor, although the power delivered is 5.5MW, to Substation 'Z'. Possibility of only one reactor being connected to Substation 'Z' is very remote but may happen under severe abnormal operating conditions to run all the critical and essential loads at Substation 'Z'.

Table 12

CLR=0.3 ohms; Source X/R ratio 4.61 and Fault level = 2789MVA at 132KV level and Cable impedance between Substation 'X' and Substation 'Z' is totally ignored (As this would represent worst condition for Ik")				
Number of Reactors in Service	Short Circuit current at Substation 'Z' 11KV Bus including down steam contributions		Maximum Current through the Reactor	
	Ip (KA)	Ik" (KA)	Ip (KA)	Ik" (KA)
Four Reactors in parallel operation (power flow 12MW)	65.798	25.87	14.382	5.64
Three Reactors in parallel operation (power flow 12MW)	61.825	24.247	17.8	6.98
Two Reactors in parallel operation (maximum power flow 8.98MW)	55.306	21.618	23.36	9.16
One Reactor in operation (Three reactors out of service) (maximum power flow 5.5MW)	42.642	16.605	34.0	13.31

From the above it can be noted that when only one reactor is in operation then Ik"current flow through reactor is highest. Hence current values pertaining to this mode of operation is relevant for sizing of all the four reactors. Accordingly, this calculated current with a safety factor can be considered as the maximum thermal short circuit current rating of the Reactor.

(b) rated thermal short circuit current may be derived from the specified short circuit power, system voltage and reactor impedance. On this aspect the following evaluation is carried out:

Assuming 132KV source impedance to be zero, the maximum steady state short circuit current at Substation 'X' 11KV bus is 27KA. This corresponds to source impedance of 0.236 ohms.

Table 13

No. of reactors in service	Total Impedance (Source impedance + Reactor impedance + cable impedance) (ohms)	Fault current at Substation 'Z' (KA)	Current seen by each reactor (KA)
4 reactors	0.236 + 0.075 +0.1 = 0.411	15.45	3.86
3 reactors	0.236 + 0.1+0.1 = 0.436	14.57	4.86
2 reactors	0.236 + 0.15 +0.1= 0.486	13.07	6.53
1 reactor	0.236 + 0.3 +0.1= 0.636	9.9	9.9

Ignoring the cable impedance between Substation 'X' and Substation 'Z' the values are tabulated here under:

Table 14

No. of reactors in service	Total Impedance (Source impedance + Reactor impedance) (ohms)	Fault current at Substation 'Z' (KA)	Current seen by each reactor (KA)
4 reactors	0.236 + 0.075 = 0.311	20.42	5.1
3 reactors	0.236 + 0.1 = 0.336	18.9	6.3
2 reactors	0.236 + 0.15 = 0.386	16.45	8.23
1 reactor	0.236 + 0.3 = 0.536	11.85	11.85

Both (a) and (b) are consistent. The values computed in (b) are steady state rms values as against values computed in (a) are initial symmetrical r.m.s values. Hence a short circuit current rating Iscr of reactor can be taken as Ik" value 13.31KA with a safety factor of additional 15% which equals to 16.64KA. Based on this rated mechanical short circuit current (Imcr = 2.55Iscr) 42.42KA is assigned.

Duty Cycle: In the subject study, network does not have any auto re-closure systems. It is expected that after occurrence of the short circuit, the general practice of fault investigation takes place before the reactor is put back into service. Accordingly duty cycle requirement is not considered in the subject study.

6. Insertion of Reactor into the electrical network and its impact:

Transient Recovery voltage: Presence of reactors in the electrical networks results in severe transient phenomena during the breaker opening conditions under fault conditions [4],[6]. As the circuit breaker operates to interrupt the fault currents (at Substation 'X' outgoing breaker for faults either in the reactor or on the cable connecting to Substation Z or at Substation 'Z' incomer breaker for 11KV bus bar faults) current chopping takes place leading to a transient phenomenon that may lead to restrike the arc between isolated poles of the circuit breaker due to a very rapidly rising voltages across the poles. This is known as transient recovery voltage and this depends upon

Circuit conditions & the parameters of the circuit

Fault current

Out of phase switching

First pole to Clear Factor and

Circuit Breaker Application

The transient recovery voltage can cause Insulation failures and/or Re-ignition and Re-strike of interrupting mediums in the Circuit breakers. In other words TRV limits the interrupting capability of the circuit breaker. If a circuit breaker is capable of withstanding TRV peak value and Rate of rise of voltage then Circuit breaker can successfully interrupt the fault conditions.

In connection with transient recovery voltage the circuit breakers are assigned with the following important three ratings:

Peak TRV in KV

Time to Peak of TRV in microseconds

Rate of Rise of Recovery Voltage (RRRV)

The TRV values are estimated in manual means by using the following formulae:

Calculation of the First Peak of TRV:

Contribution of the line side voltage (eL):

$$eL = d\,(1-M) \times 0.816 \times Ur$$

Ur is the rated maximum voltage = 11KV

M is the ratio of fault current to the rated short circuit current

d (peak factor) is dependent on ratio of surge impedance Zo/Z1, assumes a value of 1.6 which is considered to be conservative.

Contribution of source side voltage (es):

$$es = 2 \times M (TL -2)$$

The time to peak TL is determined by the following equations:

$$TL = eL/RL$$

$$RL = 1.414\ wzMI$$

RL is the rate of rise (KV/µs)

TL is the time to peak (µs)

I rated short circuit current (KA) (40KA)

Z is the surge impedance considered as 50 ohms

$$TRV = es + eL$$

Applying the above equations the following values of TRV and RRRV for Substation 'X' (11KV, 40KA breaker) are computed for various operating conditions:

Table 15

Number of reactors in service	One reactor clearing fault current (Rounded off) in KA	Transient Recovery voltage (TRV in KV)	RRRV KV/µs
Four Reactors	4	41.54	0.287
Three Reactors	5	40.15	0.356
Two Reactors	7	37.8	0.5
One Reactor	10	34.125	0.701

Applying the above equations the following values of TRV and RRRV for Substation 'Z' (11KV, 25KA breaker) are computed for various operating conditions: (in this case also surge impedance is taken as 50ohms, in reality the surge impedance could be different as the bus bars and its configuration in Substation 'Z' would determine the surge impedance).

Table 16

Number of reactors in service	One reactor clearing fault current (Rounded off) in KA	Transient Recovery voltage (TRV in KV)	RRRV KV/µs
Four Reactors	4	38.63	0.454
Three Reactors	5	36.6	0.565
Two Reactors	7	32.41	0.783
One Reactor	10	26.45	1.089

From the above it can be seen that in both Substations X & Z TRV values are more than the acceptable standard values of IEC 62271-100. A critical assessment is necessary with the aid of transient analyzer program for quantifying other values of TRV. It is expected that in all these cases the calculated values will be more than the standard TRV values indicated in the IEC 62271-100. It is known that as the short circuit current decreases the TRV peak value increases and Time to peak will reduce thus increasing RRRV. As the estimated TRV values are more than specified class S1 circuit breakers of IEC62271-100 the following are the ways of mitigation:

Provide appropriate size of capacitance to the circuit breaker terminals or across the terminals or increase the internal capacitance of the reactor (manufacturer of the reactor can make proper proposal on appropriate method of mitigation).

The impact of large capacitor bank at Substation 'Z' meant for power factor improvement at 11KV bus needs to be assessed as to how these capacitor banks would effect TRV values and its mitigation at the circuit breakers of the Substation 'X' and Substation 'Z'. The 11KV system is resistance grounded at the transformer end. First pole to clear factor is dependent on the system grounding. The subject study has not reviewed how the resistance grounding at 11KV of Substation X would impact the TRV values if the terminal faults happen.

Use higher voltage or higher current rating circuit breaker to handle the estimated value of TRV. This method is costly and is not practicable in the subject study.

Resonance: The network under study has series limiting reactor between Substation 'X' & Substation 'Z' and capacitor banks at Substation 'Z', there is a possibility that both series and parallel resonance may be generated. Further harmonics are also present in the network. Harmonics present in the network may generate resonance conditions apart from the TRV related resonance and mitigation capacitors across the reactor may also have on resonant conditions. All the resonance issues will be studied and presented in a separate paper in due course of time. Any resonant condition in the electrical network is detrimental as series resonance will result in high harmonic currents and parallel resonance will result in high voltages & currents resulting in damage of equipment.

Current Harmonics Impact on Reactor: Harmonics in the applied voltage and nonlinear magnetic characteristic of the reactor results in harmonic currents that would cause additional heating of the reactor over and above normal heating that would occur from the fundamental current. In the subject study, the harmonic distortion VTHD is less than one (1) percent at Substation 'X', and reactor being oil filled type, it is assumed that heating due to harmonic current will not be detrimental for the continuous operation of the series current limiting reactors through the life of the reactors.

7. Conclusion:

Although 0.3 ohm and 0.5 ohm value reactors appear to be acceptable from load flow, voltage regulation, short circuit and motor starting aspects, choice of 0.5 ohm reactor is not correct that would lead to less efficient electrical network from the energy conversation. Also, high reactor impedance means more copper content, bigger foot print and higher cost.

In the above study it is brought out that, with the higher short circuit current rating & higher time withstand rating of the short circuit current of the reactor, issues pertaining to testing would crop up as the reactors testing may not be feasible due to limitations of testing houses. This is particularly the case with the reactors at 11KV voltage level as the testing of the reactors for full rating currents may not be feasible.

After the impedance value of the reactor is finalized, evaluation of Transient Recovery Voltage related aspects is very much necessary to verify the capability of installed circuit breaker to isolate the fault current under various operating conditions. Where ever the calculated TRV ratings cross the limits of the installed circuit breaker rating, mitigation measures are necessary. It can be noted that if higher impedance reactor value is chosen it is likely that peak TRV values further increase as the short circuit current will further reduce.

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