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Grid connection to CPP in a deregulated electricity market: A case study related to fault current levels

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Abstract: Cost of power is one of the major driving factors for profit margins in any industry. Deregulation of electricity market enhances this opportunity for industry consumers to settle for minimum prices for the same usage of electricity. This leads to restructuring of existing power system networks. Addition of infinite power sources such as grid, demands for a thorough check of design limits of the available switchgear. Thus, short circuit current levels become a deciding factor in importing additional power with existing switchgear. In a Captive Power Plant (CPP), the maximum fault current levels are studied with respect to single phase to ground fault (Line to ground – LG) and three phase short circuit fault. Methods of grounding determine whether LG fault current can exceed the three phase fault current. This becomes necessary as the estimated maximum current is used for deciding the rated short circuit breaking capacity of switchgear. LG fault currents are computed and compared with three phase fault currents at different system voltage levels for a particular CPP where power import from grid is considered. An attempt is made to study the variation of Coefficient of grounding with system grounding resistance for a particular voltage level which is resistively grounded.

Keywords: *Coefficient of grounding, High resistance grounding, Low resistance grounding, Sequence impedance, Single/three phase faults, Short circuit current, Solidly earthed.*

1.0 INTRODUCTION

Recent developments related to deregulation of electricity prices are encouraging power import (or export) from (to) the grid. This in turn increases the fault levels in the CPPs, at times necessitating retrofitting of circuit breakers and restructuring of power systems. Grid connection provides industries with opportunities to maximize their profits under deregulated electricity market. Addition of infinite power sources such as grid impacts the existing electrical system to a huge extent as the same needs to be cross-checked for its withstand capacities [1]. Hence, short circuit analysis becomes an important study that needs to be carried out.

Short circuit study helps in determining the fault current magnitudes at various system levels in the network. These values are then used for determining the rated short circuit breaking capacity of the circuit breaker as well as the ratedshort circuit withstand current of associated switchgear. The results of short circuit studies are also used in relay coordination study as it helps in determining accurate operation of protection system.

Factors affecting fault levels are mainly impedances of sources of power–generators/grid, transformers and the rotating loads. Other factor of importance is the location of fault [2] (fault near the generator or those far away from the generator/source).

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Fault calculations are carried out using the symmetrical components method [3]. Three phase faults being balanced in nature use only positive sequence components. On the contrary, LG faults are unbalanced in nature and hence the analysis comprises of sequence components (both negative and zero sequence components). The zero sequence impedances are the ones which are mainly affected by the method of neutral grounding. Hence, the methods of neutral grounding influence the LG fault current magnitudes [2]. The various methods in which generator and transformer neutral can be grounded are, (i) solidly grounded, (ii) low-resistance grounded, (iii) high- resistance grounded, (iv) reactance grounded and (v) ungrounded [4].

The CPPs are designed so as to supply power to loads which are predominantly motor loads. Load requirement dictates the need for single or multiple generators. Depending on the number of generators, grounding can be single point grounding or multiple point grounding [4]. Based on number of grounding points, the magnitude of fault currents increases as impedance of ground path reduces due to parallel addition of impedances.

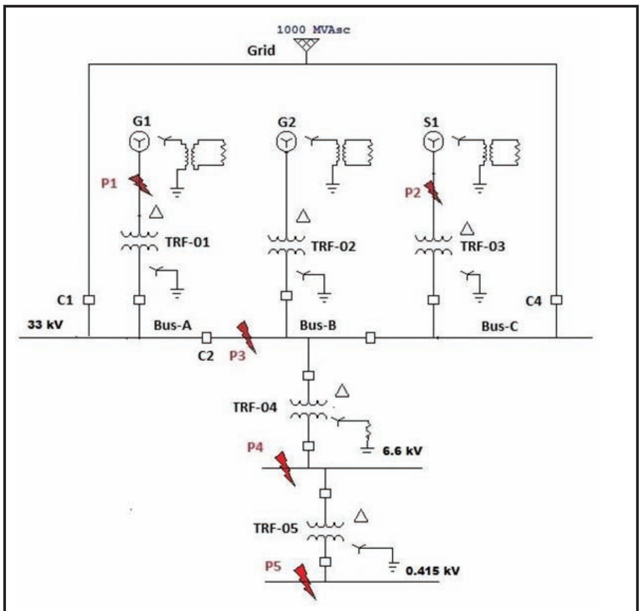

FIG. 1 SINGLE LINE DIAGRAM OF CAPTIVE POWER PLANT UNDER STUDY

These CPPs can run either in an islanded mode or in parallel operation with grid. When a source is added to the network, the fault currents increase [5]. Addition of grid to the system increases the fault levels to a much higher extent as discussed in this paper. Hence, during restructuring of system for import/export of power from the grid, short circuit fault current levels are to be rechecked.

Short circuit studies should primarily include three phase faults and single line to ground faults. LG faults are the most common faults in the electrical network as they constitute 75-80% of the total fault occurrence in the system. According to the common knowledge, three phase faults are considered to be the most severe of all the faults. However, there are situations where the three phase fault currents are lesser in magnitude than that of single phase faults [6-7]. Thus special attention is given to LG faults and three phase faults in the CPP in this paper.

The objective of the present study is to understand the increase in fault current level due to addition of grid to a CPP. The study is focused on three phase and single phase faults so as to identify the maximum fault current level. This computed maximum fault current is compared with withstand capacities of the existing switchgears of the CPP. Also, variation of coefficient of grounding (COG) is studied with respect to resistive grounding at 6.6 kV voltage level of the CPP, which helps to control the LG-fault current level.

2.0 CAPTIVE POWER PLANT DETAILS

The CPP under study is of 72 MW generation capacity. It consists of three generators G1, G2 and S1. Generators G1, G2 are gas turbine units of 22 MW each and S1 is a steam turbine unit of 28 MW. The load catered (connected load) is 40 MW. The generating voltage is 11 kV. This voltage is further stepped up to 33 kV by means of individual generator transformers TRF-01, TRF-02 and TRF-03 as indicated in Figure 1. The 33 kV buses, (Bus A, Bus B and Bus C; see Figure 1) are the three distribution buses. The power is distributed to 9 localized substations. One such typical distribution radial feeder is shown in Figure 1, where 33 kV is stepped down to 6.6 kV by means of a step down transformer, namely TRF-04. High tension motors are connected to this 6.6 kV bus. To cater low tension motors and other loads, the voltage is further reduced to 0.415 kV by means of another step down transformer, namely TRF-05.

As seen in Figure 1, there are two separate grid lines that are available at 33 kV synchronizing with CPP at Bus A and Bus C. The grid power is fed to the network when circuit breakers C1 and C4 are closed. The bus-couplers C2 and C3 are normally kept closed ensuring power flow to 33 kV bus through any of the generating units/ grid.

A. Neutral grounding:

The type of grounding determines the maximum fault current level in the system. Either resistor or reactor can be used to limit the fault currents involving ground. Resistive grounding methods only are discussed in the paper (since such grounding is prevailing in this CPP). Based on the magnitude of the current limited by resistor, grounding can be classified into high resistance grounding or low resistance grounding. The neutral grounding resistor used for limiting the fault current can either be directly connected to the generator neutral or through a secondary of a single phase neutral connected to the grounding transformer [8]. The current through such a primary of the neutral grounding transformer for a single phase to ground fault on a generator terminal is usually limited to a magnitude between 5 A and 15 A. This can be achieved with sequence capacitance to ground in the circuit operating at generator voltage [9].

As the fault current level is restricted to a very low value, the protection systems used for high resistance systems are usually for detection and alarm only, rather than trip-out [10]. The LG fault current magnitude in this type of grounding is usually less than 0.1% of three phase fault current [11]. In low resistance grounded systems, the ground fault current is typically between 100 A and 1000 A [10]. Solidly grounded systems are used to limit the probable rise in phase-to-ground voltages [12].

The captive power plant under study is an excellent example for demonstration of use of all the types of grounding methods employed for single power system network. The generator neutrals are of high resistance grounding. The grounding is achieved by means of a neutral grounding transformer resistor (NGTR). The step up generator- transformers, (TRF-01, TRF-02, and TRF-03) of 11 kV / 34.3 kV, delta-wye configurations are solidly grounded. The transformers at 33/6.9 kV, (typical one among 10 of them is as shown in Figure 1; TRF-04) are low resistively grounded. Transformers at 6.6 kV / 0.433 kV, (typical one shown in Figure 1; TRF-05) are solidly grounded. Thus, this CPP has three types of grounding, namely, (i) solidly grounded, (ii) high resistance grounded, and (iii) low resistance grounded.

B. Coefficient of grounding (COG):

It is defined as ratio of highest line to ground voltage of the healthy phases during a single line to ground fault to the normal line to line system voltage [13].

$$COG = \frac{V_{LN}}{V_{LL}} \quad ...(1)$$

where V_{LN} is the maximum line to ground voltage and V_{LL} is the normal line to line voltage. COG can also be defined in terms of sequence impedances as given by equation (2) (here in present study, the positive sequence impedance Z1 nearly equal to the negative sequence impedance Z2)

$$COG = \left| -\left(\frac{1}{2}\right) * \left(\frac{k\sqrt{3}}{2+k} \pm i\right) \right| \quad ...(2)$$

where k is defined as per equation (3).

$$k = \frac{Z0}{Z1} \quad ...(3)$$

where Z0, Z1 are the net zero sequence and positive sequence impedance of the system at the point of fault, respectively [13]. COG of effectively grounding system is less than 0.8 [13]. appropriate resistor depending upon generator size and zero-

3.0 OPERATION OF THE PLANT

The operating scenarios of this power plant (CPP) can be grouped into two: (i) islanded operation (ii) parallel operation with grid. Thus, these two operating scenarios which involve all the generators of the CPP are listed in Table 1.

TABLE 1
OPERATING SCENARIOS OF CPP WITH REFERENCE TO PARALLEL OPERATION OF AVAILABLE SOURCES.

Case study	Combination of sources
Case-01	G1 + G2 + S1
Case-02	G1 + G2 + S1 + Grid

The per unit (pu) sequence impedances of generators and transformers (shown in Figure 1) on its own MVA base and kV base along with their ratings are available. These are used in the present calculations. All the calculations are done using MATLAB with appropriate coding. These results are also cross-checked using ETAP.

4.0 COMPUTATION OF FAULT CURRENTS AND COEFFICIENT OF GROUNDING

Faults are computed at different voltage levels in the system to check the feasibility of the overall electrical network. Hence, faults are considered at the locations P1, P2, P3, P4 and P5 marked in Figure 1. At these same points, coefficient of grounding is also calculated to cross-check the type of grounding as per definitions given in literature [13].

a) Fault current calculations

For ease of calculations, per unit method is used for calculating the fault currents. Also, all the equipment MVA and voltage ratings are converted to a base MVA, and base kV. In this study, base MVA is 100 MVA and equipment voltage rating is the base kV [6], [14].

Cable impedances (except grid) and motor contribution to the fault current are neglected in the present study.

b) Coefficient of grounding calculations

The COG is calculated using equation (2) and (3) at all the system voltage levels prevalent in the CPP. In low resistance ground case of 6.6 kV, the effect of magnitude of neutral grounding resistance on COG is also studied.

5.0 RESULTS AND DISCUSSIONS

The computed fault currents for three phase and LG faults for islanded operation of CPP are tabulated in Table 2. The fault currents at point P3 (see Figure 1) are in the order of kA. An interesting point to be noted is that LG fault current magnitude is higher than the three phase fault current, contrary to the common thinking that three phase faults are more severe.

For parallel operation with grid, fault currents computed for LG and three phase faults are listed in Table 2. These fault

currents are one order higher compared to the corresponding cases of islanded operation at all the 5 typical locations (P1 to P5 considered) for the 3-phase faults. As the impedance offered to the fault current with grid is low compared to that of CPP alone, the fault currents increase greatly for three phase faults. For single phase faults the fault current magnitude increases significantly only at locations P3 and P5, which adopt solid grounding. Thus, cross-check of withstand capacities of existing switchgear becomes a deciding factor in importing of power from the grid.

For fault at P4, LG fault current is restricted to 420 A as indicated in Table 2. Thus, this type of grounding is classified as low resistance grounding as the fault current is restricted within 1000 A [10]. Variation of LG fault current with grounding resistance is depicted in Figure 2. These results are obtained using MATLAB as the tool. The single phase fault current magnitude increased to an order of kA for resistor value of 0 Ω (Figure 2). As resistor value is increased from 0 Ω to 20 Ω, the LG fault current magnitude decreased from 8.5 kA to 208

TABLE 2			
FAULT CURRENTS AT DIFFERENT SYSTEM VOLTAGE LEVELS WITHIN THE CPP.			
Fault location	**Voltage level** (kV)	**LG fault current** (kA)	**3 phase fault** current (kA)
Without grid connection			
P1	11	0.01	19.40
P2	11	0.01	13.45
P3	33	7.12	6.25
P4	6.6	0.42	7.86
P5	0.415	42.66	38.51
With grid connection			
P1	11	0.01	23.45
P2	11	0.01	15.53
P3	33	20.53	18.84
P4	6.6	0.42	9.45
P5	0.415	44.76	40.74

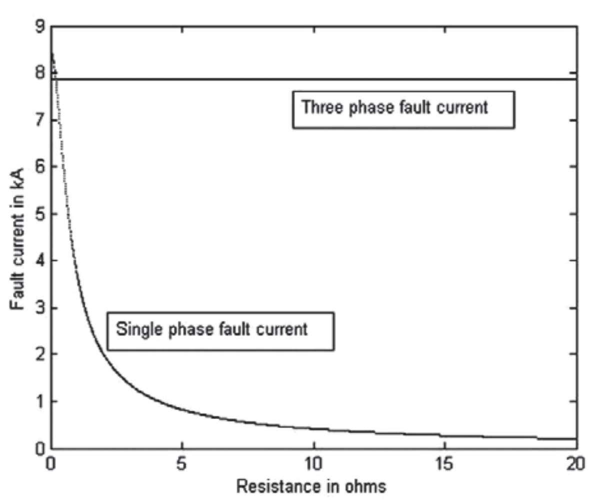

FIG. 2 VARIATION OF LG FAULT AND THREE PHASE FAULT CURRENT WITH NEUTRAL GROUNDING RESISTANCE OF 6.6 KV SYSTEM.

A. Thus, effect of adding resistance to the neutral has significant impact on the LG fault current magnitude.

At this point it is to be noted that for solidly grounded systems, magnitude of LG fault current is more than three phase fault current. Hence, it can be concluded that by using appropriate grounding technique, LG fault current magnitude can be reduced to a desired value.

However, as expected, it doesn't reduce the value of three phase fault current magnitude. To reduce three phase fault currents, high impedance components such as transformers may have to be included.

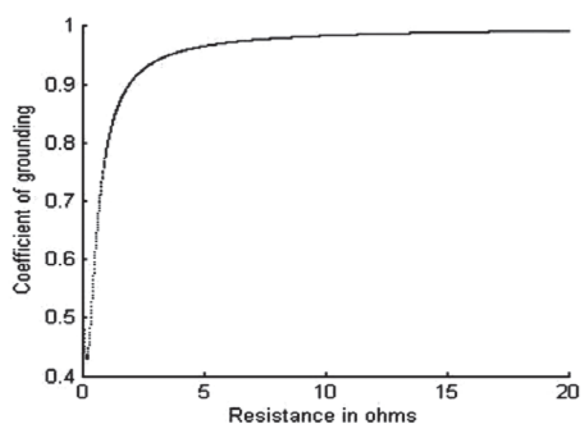

FIG. 3 VARIATION OF COG WITH NEUTRAL GROUNDING REISTANCE OF 6.6 KV SYSTEM.

For the system voltage level of 0.415 kV, as the system is solidly grounded, LG faults are severe than three phase faults (location P5). The fault current withstand capacity of 0.415 kV switchgear is 65 kA as mentioned in Table 3. This being higher than maximum fault current level even after grid connection, grid connected operation is feasible.

The LG fault current is restricted to 10 A for fault considered at locations P1 and P2. This is classified as high resistance grounding as per IEEE standard [10]. Grid connection increases the three phase fault current level to 23.35 kA and 15.53 kA at P1 and P2, respectively. As fault current is much less than the rated withstand capacity of 40 kA (Table 3), retrofit of switchgears in CPP is not required.

The circuit breakers and other switchgear such as bus bars at the 33 kV level have rated short circuit withstand capacity of 31.5 kA. This withstand level is higher than the worst case (case-02; grid connected) where the fault current is 20.53 kA (Table 2). Hence, the same switchgear of 33 kV can serve in the augmented system.

The maximum value of the three phase fault current for 6.6 kV system increases to 9.45 kA (Table 2) which is well within the limits of the switchgear withstand capacity of 31.5 kA for 6.6 kV system (Table 3).

Coefficient of grounding is computed at different voltage levels using the magnitudes of Z0 and Z1. As the system becomes high resistance grounded system, the value of COG increases from 0 to 1. On the basis of LG fault current, the 11 kV system was identified as high resistance grounded. As seen from Table 4, the value of COG at point P1 and P2 is 0.998 implying high resistance grounding. Also, the value of COG at 6.6 kV is 0.98 which implies that the system is non-effectively grounded. For solidly grounded systems like 33 kV and 0.415 kV, the value of COG is 0.52 and 0.55 as listed in Table 4.

TABLE 3

COEFFICIENT OF GROUNDING AT DIFFERENT VOLTAGE LEVELS

Sl no	Voltage Level	COG
1	11 kV (P1)	0.998
2	11 kV (P2)	0.998
3	33 kV	0.52
4	6.6 kV	0.98
5	0.415 kV	0.55

The corresponding variation in the fault currents at 6.6 kV can be seen from Figure 2. The changes in neutral grounding resistance result in the changes in COG as shown in in Figure 3. As the resistance is increased from 0 to 20 Ω, the COG increases from 0 to 1 indicating that the effectively grounded system becomes non-effective grounded system [13]. This aspect becomes important not only for the controlling the fault current levels of LG faults but also for the insulation coordination and choosing the appropriate over voltage protection devices.

The value of neutral grounding resistance of 6.6 kV system of the CPP is calculated empirically for the condition when the magnitude of LG fault current becomes equal to magnitude of three phase fault current. For the neutral grounding resistance values greater than 0.17 Ω the LG faults currents are lower than the 3-phase fault currents. The corresponding value of COG for this value of resistance is 0.42.

6.0 CONCLUSION

Import of power from the grid increases the fault levels at all the voltage levels in the CPP including 11 kV, 33 kV, 6.6 kV and 0.415 kV as 3-phase fault currents increase. Since the maximum fault levels are within the withstand capacity of the switchgear, retrofitting is not required. Thus grid connected operation of CPP is feasible.

TABLE 4

WITHSTAND LEVELS OF SWITCH GEAR FOR DIFFERENT VOLTAGE LEVELS

Sl no	Voltage level (kV)	Fault level (kA)
1	11	40
2	33	31.5
3	6.6	31.5
4	0.415	65

The single phase-to-ground (LG) fault current exceeds the corresponding three phase fault current in cases where the system is grounded solidly, contrary to the logical thinking.

Also, over the range of neutral grounding resistor values from 0 to 20 Ω, the LG fault current decreases to an order from kA to few Amperes. Thus choice of magnitude of resistor, if included in neutral, gives some control over LG-fault current.

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