Impact of Coupling Breakers in a Power Plant Fault Analysis

Levent KILIÇ[1], Ayşen BASA ARSOY[2]

1 Türkiye Şişe ve Cam Fabrikaları A.Ş., 34330, Levent, Istanbul
2 Electrical Engineering Department, Engineering Faculty, Kocaeli University, 41100, Kocaeli
lkilic@sisecam.com, aba@kocaeli.edu.tr

Abstract

Over the last decades, the private sector power plants are integrated into the power system with growing number and size. Since these power plants are large, their impacts on the grid are strong as well. The steady state and transient analyses required for plant connection to the grid, mostly play a role in the selection of the equipment and determination of the protection settings. Installation and commissioning of power plants based on accurate analyses are of great importance in raising the reliability of the system. The number of generating units in a power plant can be increased for capacity expansion. The coupling breakers (bus tie breakers) are used in plant substations configured in double bus scheme. Each generator are connected to the grid through these buses having the coupling breaker in a closed/opened position. This study investigates the impact of these breakers in terms of short circuit faults by using a real data obtained from the natural gas power plant connected to the 154 kV grid through overhead transmission line. Fault currents are computed based on IEC 60909 and compared for different status of coupling breakers.

1. Introduction

Power plants are expensive investments. As they will be connected to the national grid, their impacts need to be well analyzed. The capacity expansion on power plants occurs frequently. As the increase in load demand feeding busbar and the change in marketing conditions to have an active role may require an additional machine to the existing structure.

Obtaining the correct data from the grid and power plant itself and also running the data correctly will increase the accuracy of the calculations. Failure to do so can not be corrected due to the change in structure, even if it is technically possible. In addition, the system operator by the grid side bring strict rules that have to be obeyed by the plant operator.

Fault analysis is used and required for grid connection criterias for all voltage levels. Short circuit calculations are decisive factors on the choice of equipment and operation for both the grid and the power plants and therefore important in planning stage.

In the literature, there are particularly the short circuit calculations for renewable energy sources in connection to the grid [1,2,3]. However, in those, the benefits of the position of the coupling circuit breaker (CCB) on operating the power plant/grid are not emphasized. In this article, this deficiency will be shown by calculating the actual operating data according to new situations.

Grid Code rules are implemented in our country for those plants which will be connected to the grid using 154 kV system [4,5]. IEC 60909 Standards enable calculations adhering to the large conventional electricity production plants on production and consumption equipment at different voltage levels, configurations and operating conditions.

Here, the comparative assessment of the results achieved by the inclusion of the correction factors will be made according to IEC 60909 methodology of the short circuit calculations of the plant connecting to the national grid through standardized TEİAŞ (Turkish Electricity Authority) switching system that will be modified by the addition of the second unit to 141.25 MVA having the same characteristics. Short circuit calculations will be helpful about leading to the required positions of the situation on the switching equipment compliance and normal/fault operations. The short circuit impact on the power plant busbar with the addition of the machine to the system will be examined. The results are expected to be beneficial to the active network operating system.

2. Review of IEC 60909 Standard

2.1. Basic Principles

IEC 60909 standard is used on short circuit calculations for 50 and 60 Hz 3-phase ac systems. The equivalent voltage source method enables fault current calculations using the system voltage and the rated voltage of the equipment. To increase the accuracy of the results, a variety of standard impedance correction factors are recommended.

Short circuit current is always considered to occur with the sum of ac symmetrical current and dc component. The main difference is between 'far from generator' and 'near to generator' failures. In far from generator short circuit, the short circuit current includes a decreasing ac symmetrical component over time, but on near to generator short circuit , this ac component remains constant. Maximum and minimum values for balanced and unbalanced short circuit faults can be calculated standard. Different approaches can be used according to the radial or mesh network structure or where the fault is.

In case of more than one power supply point of failure on the network, the total fault current will consist of the vectoral sum of the all currents from all sources. The grid with some different earthing structure, like a single- phase, short circuit faults may have the highest values.

2.2. Short Circuit Current Definitions

Initial symmetrical short circuit current is the effective (rms) value of I''_k ac symmetrical component. Known as initial fault level, the short circuit power S''_k

$$S''_k = \sqrt{3}\, I''_k\, U_n \quad (1)$$

is defined as above. U_n is the nominal voltage on the short circuit point.

The characteristics values of various effects of the reduction in short circuit current over time is described briefly below [6]:

Short circuit current peak value , i_p , is described as the maximum instantaneous value of the fault current.

$$i_p = \kappa \sqrt{2}\, I''_k \quad (2)$$

κ factor is given by the following expression:

$$\kappa = 1.02 + 0.98\, \mathrm{e}^{-R/X} \quad (3)$$

R and X are the real and imaginary impedance components at the point of the short circuit impedance Z_k.

The short-circuit current decaying non-periodic component of i_{dc} is defined as the average of the lower and upper curve.

$$i_{dc} = \sqrt{2}\, I''_k\, \mathrm{e}^{-2\pi f t R/X} \quad (4)$$

f nominal frequency , t the time, also R/X have the same ratio in the equation (3). Symmetrical short-circuit break current is the rms value of the symmetrical ac component at the time of contact seperation current of the first pole of the I_b switching equipment.

In case of near to generator short circuits, I_b is assumed to equal to I''_k. The symmetrical breaking currents of synchromous and asynchronous machines (generators or motors) are respectively,

$$I_b = \mu\, I''_k \quad (5)$$

$$I_b = \mu\, q\, I''_k \quad (6)$$

μ factor is I''_k / I_{rG} ratio. I_{rG} is synchoronous machine rated current. Factor q is P_{rM} /p ratio. P_{rM} shows machine asynchronous active power, p shows pole pairs of the asynchoronous machine. Both factors depend on the considered minimum breaking time, t_{min} and diagrams are provided in the IEC standard. A safe approximation can be taken as μ=1 ve μq=1.

The steady state short circuit current , I_k, is the rms value after the decay of the transient components.

For generators,

$$I_{k\max} = \lambda_{\max}\, I_{rG} \quad (7)$$

λ_{max} factor is obtained as graphicaaly. For far from generator faults, $I_k = I''_k$.

Thermal equivalent short circuit, I_{th}, is defined as the rms value of the nondecaying current.

$$\int_0^{T_k} i^2 dt = I''^{\,2}_k\, (m+n) = I_{th}^2\, T_k \quad (8)$$

T_k is the time of the short circuit current. m and n factors are obtained as graphically and are used for the thermal effect of the dc and ac component respectively.

2.3. Initial Short Circuit I''_k Calculation

Using IEC 60909 calculation method and $\frac{c\, U_n}{\sqrt{3}}$ equivalent voltage source , the currents are determined at F fault point. Equivalent voltage source will be used on positive component system. All the other sources in the system are removed.

The equivalent voltage source method is shown in Figures 1 and 2 . c voltage factor , taking into account the system voltage changes , shows the permissible voltage drop on the grid. When calculating maximum short circuit currents, the value c_{max}=1.1 is recommended for all voltage levels.

$$I''_k = \frac{c\, U_n}{\sqrt{3}\, Z_k} \quad (9)$$

Here, Z_k is the short circuit impedance value (Thevenin's impedance) at the short circuit point. In the unbalanced short circuit situations, calculations can be done with the symmetrical component method. The highest current value depends on the $\underline{Z}_{(1)}, \underline{Z}_{(2)}, \underline{Z}_{(0)}$ impedance components at the fault point. Here , 1,2 and 0 respectively correspond to the positive, negative and zero component values . When it is $\underline{Z}_{(0)} > \underline{Z}_{(1)} = \underline{Z}_{(2)}$ for example ,at the high voltage/ medium voltage switchgear centers where medium voltage side is grounded through the resistance, the highest current is in the form of 3-phase short circuit. The Networks with different neutral earthing schemes , unbalanced earth faults may provide the highest current.

2.4. Short Circuit Impedances

The equivalent voltage source is defined as $\frac{c\, U_n}{\sqrt{3}}$ in the previous part. This is the only source in the system. On calculations, grid, all synchronous and asynchronous machines are replaced by their internal impedances.

Q, T, G and M indices , respectively, correspond to grid, transformer, synchronous generator and asynchronous motor definition, r and n sub-indices , rated values.

Equivalent impedance of the grid $\underline{Z}_Q = R_Q + jX_Q$

$$\underline{Z}_Q = \frac{c\,\mathrm{U_{nQ}}}{\sqrt{3}\,I''_{kQ}} \quad (10)$$

IEC Standard offers $R_Q = 0$ for the grids over 35 kV voltage level. For all other situations, taking $\frac{R_Q}{X_Q} = 0.1$ would be safe approach.

The short circuit impedance $\underline{Z}_T = R_T + jX_T$ of a transformer with or without an on load tap changer is calculated using:

$$Z_T = \frac{u_{kr}}{100}\frac{\mathrm{U_{rT}^2}}{\mathrm{S_{rT}}} \quad (11)$$

$$R_T = \frac{u_{Rr}}{100}\frac{\mathrm{U_{rT}^2}}{\mathrm{S_{rT}}} = \frac{P_{krT}}{3\,\mathrm{I_{rT}^2}} \quad (12)$$

$$X_T = \sqrt{Z_T^2 - R_T^2} \quad (13)$$

u_{kr} is the short circuit voltage of the transformer. u_{Rr} is the resistive component of the short circuit voltage and P_{krT} is the load losses at rated current. The equation can be also applied for the (11)- (13) short circuit limiting reactors . The $\underline{Z}_L = R_L + jX_L$ impedance value of overhead lines and cables can be calculated through line geometry and it is known for standard for line types.

The impedance value for synchronous generator is replaced by equation (14) where X''_d is a subtransient reactance.

$$\underline{Z}_G = R_G + jX''_d \quad (14)$$

Synchronous generators connected to the grid through unit transformer , the impedance for high voltage side for power plants , t_r , shows the transformation ratio .

$$\underline{Z}_S = t_r^2\,\mathrm{Z_G} + \underline{Z}_{THV} \quad (15)$$

The impedance $\underline{Z}_M = R_M + jX_M$ of asynchronous motor is given by

$$\underline{Z}_M = \frac{1}{\frac{I_{LR}}{I_{rM}}}\frac{\mathrm{U_{rM}}}{\sqrt{3}\,\mathrm{I_{rM}}} = \frac{1}{\frac{I_{LR}}{I_{rM}}}\frac{\mathrm{U_{rM}^2}}{\mathrm{S_{rM}}} \quad (16)$$

$\frac{I_{LR}}{I_{rM}}$ shows the ratio of the locked-rotor current of the machine.

The ratio R_M / X_M ratio can be evaluated from equivalent circuit. Typical values can also be evaluated depending on the rated power and voltage of the motor. If multi- voltage level is present , voltages, currents and impedances are converted according to the voltage level at the short circuit point.

2.5. Correction Factors

IEEE 60909 introduces impedance correction factors for transformers (K_T), synchoronous generators (K_G) and power plant units (K_S ve K_{SO}).

$$K_T = 0.95\,\frac{c_{max}}{1 + 0.6x_T} \quad (17)$$

$$K_T = \frac{U_n}{U^b}\frac{c_{max}}{1 + x_T(I_T^b / I_{rT})\sin\varphi_T^b} \quad (18)$$

$$K_G = \frac{U_n}{U_{rG}}\frac{c_{max}}{1 + x''_d \sin\varphi_{rG}} \quad (19)$$

$$K_S = \frac{U_{nQ}^2}{U_{rG}^2}\frac{U_{rTLV}^2}{U_{rTHV}^2}\frac{c_{max}}{1 + \left|x''_d - x_T\right|\sin\varphi_{rG}} \quad (20)$$

$$K_{SO} = \frac{U_{nQ}}{U_{rG}(1 \pm p_G)}\frac{U_{rTLV}}{U_{rTHV}}(1 \pm p_T)\frac{c_{max}}{1 + x''_d \sin\varphi_{rG}} \quad (21)$$

Equations (17) is simplified form of Equation (18), derived from statistical data of transformers. Equations (20) and (21) are used for power plant units with transformers equipped with on load and off load tap changers, respectively. The voltage factor c_{max} in Equations (17)-(21) is determined according to the equipment rated voltage. The factor $(1 \pm p_G)$ corresponds to the maximum and minimum transformation ratio. In Equation (18) sinφ is positive for a lagging power factor of the transformer. In Equations (19)-(21) sinφ is positive for a leading power factor of the generator. Various approximation are applied to derive these expressions (such as R<<X)

$$\sqrt{1 + 2x''\sin\varphi + x''^2} = 1 + x''\sin\varphi.$$

3. Case Study

Operating the grid effectively will be possible if the working conditions of the connected plants with increasing in number, power size and variety is analyzed. To do this, the data regardless of changing structure should be based on the calculations, increasing the grid reliability according to the switching, considering the private sector plants as a part of the whole will provide maximum mutual benefit.

Here, classical calculation method is used for changed short circuit calculations on a single unit, firstly established as a 141.25 MVA cogeneration power plant which then increased to two units considering the IEC correction factors, the case change has been defined and these cases are analyzed according to the switching operation state of the coupling circuit breaker (CCB) on the power plant busbar.

When creating the grid criteria, considered (n-1) connection criteria, on the power plants that have several machines, forms faulty openings disabling the entire system bringing negativity to the system reliability.

Given the data supplied from the power plant in Table 1 and calculated impedances in Table 2, several different switching cases are analyzed for three phase, one phase-ground and two phase faults:

Table 1. Grid and Power Plant Data

Grid	$U_n = 154\,kV$, $S''_{kQ} = 2587\ MVA$
Transformer	$S_T = 157\ MVA,\ u_k = \%12.51$, $t_r = 162/15\ kV,\ YNd1$
Generator	Synchronous Generator, $2*\ 141.25\ MVA$, $\cos\phi_G = 0.8,\ U_n = 15\ kV$, $x''_{d1} = \%13.2,\ x''_{d2} = \%12.9, x''_{d0} = \%8$
Overhead Line	795 MCM Overhead Line Two Circle $l = 28.2\,km, x_L = 0.315\,\Omega/km, r_L \cong 0$

1st Case: One unit

2nd Case: Second unit is added, CCB is closed

3rd Case: Second unit is added, CCB is opened

4th Case: Third unit is added, CCB-1 closed, CCB-2 closed

5th Case: Third unit is added, CCB-1 closed, CCB-2 opened

6th Case: Third machine and line are added, CCB-1 opened, CCB-2 opened

Table 2. Calculation Methods and Results

$S''_{kQ} = \sqrt{3}\,I''_k\,U_n = \sqrt{3}\ .\ 9.7\ .\ 154 = 2587\ MVA$ $X_Q = 1.1\frac{154^2}{2587} = 10.08\ \Omega\ ; X_L = 0.315.28.2 = 8.88\ \Omega\ ;$ $X_T = \frac{12.51}{100}\frac{154^2}{157} = 18.89\ \Omega$ $X_{G1} = \frac{13.2}{100}\frac{154^2}{141.25} = 22.16\ \Omega\ ; X_{G2} = \frac{12.9}{100}\frac{154^2}{141.25} = 21.66\ \Omega\ ;$ $X_{G0} = \frac{8}{100}\frac{154^2}{141.25} = 13.43\ \Omega$
Corrected by Correction Factor;
$K_S = \frac{1.1}{1+(x''_d - x_u).\sin\varphi_G} = \frac{1.1}{1+(0.132-0.1251).0.6} = 1.095$
$X_{G1} = 1.095.22.16 = 24.27\ \Omega\ ; X_{G2} = 1.095.21.66 = 23.72\ \Omega\ ;$ $X_{G0} = 1.095.13.43 = 14.71\ \Omega$ $X_T = 1.095.18.89 = 20.68\ \Omega\ ; X_{T0} = 1.095.16.54 = 18.11\ \Omega$
$X_{T0}/X_1 = 0.8; X_{T0} = 0.8\ .20.68 = 16.54\ \Omega$ $X_{L0} = 3.5\ .X_{1H}\ ; X_{L0} = 3.5.8.88 = 31.08\ \Omega$ $X_{Q0} = 2.5\ .X_1\ ; X_{Q0} = 2.5.10.08 = 25.20\ \Omega$

Table 3 shows the corrected and uncorrected impedance positive, negative and zero values.

Table 4 shows the calculation results according to these values.

The results of the analyses can be drawn as follows;

- Correction factor decreases the short circuit current,
- CB selections are suitable for the existing and additional position,
- As short circuit currents are under the values of the Grid Regulation, CCB open/close position will not cause a problem,
- But when CCB is opened, short circuit current decreases more, and this will reduce the negative effects of the unnecessary openings of the units,
- When CCB is opened, more plants can be connected to the existing substation considering the short circuit,
- When CCB is closed, the all plant might be disabled when the short circuit is occured on the plant busbar, this will have a negative effect on the grid reliability,
- The relay settings, set to the values of the CCB is opened status, the switching can be available on appropriate values,

Table 3. Impedance Results

Case	$Z_{(1)}$	
	Uncorrected	Corrected
1st	10.73	10.97
2nd	8.50	8.82
3rd	12.16	12.53
4th	7.04	7.37
5th	9.38	9.80
6th	11.54	11.91
Case	$Z_{(2)}$	
	Uncorrected	Corrected
1st	10.69	10.94
2nd	8.46	8.78
3rd	12.10	12.48
4th	7.00	7.33
5th	9.32	9.74
6th	11.49	11.86
Case	$Z_{(0)}$	
	Uncorrected	Corrected
1st	11.76	12.54
2nd	6.87	7.41
3rd	12.27	13.13
4th	4.85	5.26
5th	7.01	7.61
6th	11.97	12.79

- When CCB is closed, instead of increasing the machine number, selecting a large size power machine will contribute to the grid reliability,
- When coupling breaker is opened, the 3 phase short circuit values are higher, when CCB is closed, the 1 phase-ground short circuit values are higher , when CCB is closed, the addition of each machine causes

24% increase on the 3 phase short circuit, but around 37% increase on the 1 phase-ground short circuit , the effect of zero component due to the grounding type,

Table 4. Short Circuit Results

Case	$I''_{k1} = \frac{\sqrt{3}\ 1.1\ U_n}{\lvert \underline{Z}_1 + \underline{Z}_2 + \underline{Z}_0 \rvert} [kA]$	
	Uncorrected	Corrected
1st	8.84	8.52
2nd	12.31	11.73
3rd	8.03	7.69
4th	15.53	14.70
5th	11.41	10.81
6th	8.38	8.03
Case	$I''_{k2} = \frac{1.1\ U_n}{\lvert \underline{Z}_1 + \underline{Z}_2 \rvert} [kA]$	
	Uncorrected	Corrected
1st	7.91	7.73
2nd	9.99	9.63
3rd	6.98	6.77
4th	12.07	11.52
5th	9.06	8.67
6th	7.36	7.13
Case	$I''_{k3} = \frac{1.1\ U_n}{\sqrt{3} \lvert \underline{Z}_1 \rvert} [kA]$	
	Uncorrected	Corrected
1st	9.11	8.92
2nd	11.51	11.09
3rd	8.04	7.81
4th	13.89	13.27
5th	10.43	9.98
6th	8.48	8.21

- Selecting two lines for each machine to provide (n-1) criteria will provide commissioning effectively, otherwise, in the case of the short circuit on the plant busbar, the whole plant may be disabled. Forming the (n-1) criteria provided for the line will be more indicative when the statistics of the plants and lines are used.
- The smaller the short circuit current , the lower size the equipment can be used, but when it increases , the use of larger size equipment will be necessary.

4. Conclusion and Suggestions

It is obvious that the plants that are connected to the national grid, increase the short circuit capacity provided on the plant/grid short circuit power. This causes restriction on the plants that connected to the grid through the same point. When the CCB position is dynamically set, improvement can be seen on these restrictions.

The plants with more than one unit, the breakdowns causing due to the grid or the plant itself, instead of total opening, individual opening, the loss of the load/production on the grid will be less.

National grid will retrieve a new structure consisting of public, private, thermic, renewables, also nuclear soon producers and sources. To operate all those different parameters effectively will be possible with participants' contributions. Positive or negative effects of the events are shared by all the participants. The technical goal should be to have the most positivity of this .

5. References

[1] Thekla N. Boutsika, Stavros A. Papathanassiou, "Short Circuit Calculations in Networks with Distributed Generation", *Electric Power System Research,* 78, pp. 1181-1191, 2008

[2] Thekla N. Boutsika, S.A. Papathanassiou,N. Drossos, "Calculation of the Fault Level Contribution of Distributed Generation Acoording to IEC Standard 60909", *NTUA Electrical Power Division Technical Paper*

[3] Jurgen Schlabbach, "Short Circuit Currents", IET Power and Energy Series 51, United Kingdom, 2005

[4] Electricity Market Grid Regulation, Official Gazette no.27418, dated 26.11.2009.

[5] Electrical Installation Project, Official Gazette no.27434, dated 16.12.2009.

[6] Short-circuit currents in three-phase a.c. systems, IEC 60909-3, 2003