ELECTROMAGNETIC FORCES DENSITIES IN 3 PHASE BUSBAR PARALLEL GEOMETRIC CONFIGURATION CONNECTED TO RECTIFIER LOAD

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ABSTRACT

All power system substations use three phase parallel busbars geometric configuration in the power distribution among loads. These busbars are subjected to electromagnetic forces (EMF) which may cause their permanent deformation, break of insulating supports and an excess vibrational stresses applied on the busbars. Among the factors that affect these forces is whether the busbars currents have harmonic content or not. This paper presents an analytical approach from which overall forces and local force densities can be calculated. Busbars currents that contain harmonics are used in this approach implementation. These currents are taken from a simulated model of 3-pulse rectifier, which is compared with an experimental model to give well qualitative current values.

INTRODUCTION

Power system substations serve as locations to step down voltage and distribute power to various locations. Normally this power is distributed by a three phase busbar structure which consists of three equally spaced parallel conductors (busbars) supported at various points by insulators. Two materials are commercially suitable for use as busbars, i.e. copper and aluminum.

It is essential that the materials used in their construction should have the best mechanical properties to operate within the temperature limits laid down in British standard or international system [1,2].

The purpose of this paper is to present an analytical approach from which forces acting on busbars may be computed. The proposed approach can also predict local force densities acting on every single busbar section in all current cases, for instant, steady state, short-circuit and harmonic cases. This paper will specify local force density calculations in case of busbars carrying harmonic currents resulting from 3-pulse rectifier.

Analysis, simulation and an experimental model of 3-pulse rectifier is done in order to notify the effect of distorted currents on the local force density applied on busbars.

Details of the approach and its implementation on 3-phase busbars connected to 3-pulse rectifier over one cycle are given in the following sections.

COMPUTATION OF ELECTROMAGNETIC FORCES (EMF)

The EMF; is the mechanical push or pull exerted on a busbar by short-circuit current and its magnetic field; i.e. it is the force tending to displace the busbars from their normal position.

The forces acting on the busbars shown in Fig.1 carrying short circuit currents depend on the geometrical configuration and the profile of the busbar [8]. The conventional arrangement of conductors in parallel and in single plane is taken as a basis for the calculation as shown in Fig. 1.

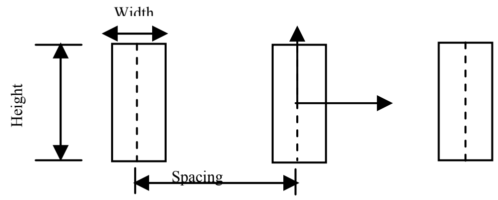

Fig. 1. Cross section of rigid busbars

A. Assumptions

- The fault is three-phase symmetrical short circuit as it causes the greatest dynamic stress [3].
- The center line distance between busbars is much smaller than the conductor length [4], and since the end effects are usually negligible in busbar application, the busbar can be regarded as being infinite length, then a 2-D field analysis can be performed assuming that the magnetic field lies in x-y plane and the currents flow along z axis.
- The permeability of copper and aluminum in air is constant.
- A steady state (not transient) balanced three phase system is applied to a three phase busbars with a peak value equal to the short circuit currents in the case of balanced three phase short circuit.
- Skin effect and proximity phenomena, which can affect the current distribution in the cross-section of solid conductor, are ignored [5].

In order to compute the forces acting on each element of the conductor, the flux density at each element must be calculated using field equations.

B. Field Equations

Biot-Savart Law: This law is used in order to determine the magnetic field due to any current carrying conductor configuration discussed in [6]. Consider busbar pair configurations shown in Fig. 2. As can be seen from this figure, arbitrary dimensions and spacing have been assumed. Given the currents flow in both busbars, local force density acting on any of them may be computed from [7] using Biot-Savart law for volume configuration. Let

$$\overline{R}_{pq} = \overline{R}_q - \overline{R}_p$$
$$= (x_q - x_p)\overline{u}_x + (y_q - y_p)\overline{u}_y - z_p\overline{u}_z$$
$$\overline{dl} = dz_p\overline{u}_z$$
$$(x_q - x_p) = X \quad \text{and} \quad (y_q - y_p) = Y$$

Where, dl is a unit length along the flow of current and $\overline{u}$ is a unit vector.

From [8], it can be shown that the flux density acting on a point (Q) enclosed in a busbar and resulting from another current-carrying busbar may be given by:

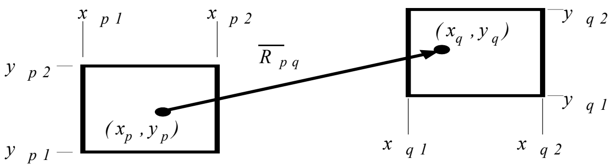

Fig. 2. Geometrical configuration of two adjacent current carrying busbars.

$$\overline{B}(x_q, y_q) = \frac{\mu_0}{4\pi}\int_{(y_q-y_{p1})}^{(y_q-y_{p2})}\int_{(x_q-x_{p1})}^{(x_q-x_{p2})}\int_{-\infty}^{+\infty} J_p dz_p\overline{u}_z \times \frac{\left[X\overline{u}_x + Y\overline{u}_y - z_p\overline{u}_z\right]}{\left[X^2 + Y^2 + z_p^2\right]^{3/2}}dXdY \tag{1}$$

From [9] it can be shown that the integrals in (1) may be further evaluated leading to the following expressions:-

$$\mathrm{B}_x(x_q, y_q) = \frac{-J_p\mu_0}{4\pi}\left[\begin{array}{l}(x_q - x_{p2})\ln\left[\frac{(x_q - x_{p2})^2 + (y_q - y_{p2})^2}{(x_q - x_{p2})^2 + (y_q - y_{p1})^2}\right] \\ + 2(y_q - y_{p2})\left[\tan^{-1}\frac{(x_q - x_{p2})}{(y_q - y_{p2})} - \tan^{-1}\frac{(x_q - x_{p1})}{(y_q - y_{p2})}\right] \\ + (x_q - x_{p1})\ln\left[\frac{(x_q - x_{p1})^2 + (y_q - y_{p1})^2}{(x_q - x_{p1})^2 + (y_q - y_{p2})^2}\right] \\ + 2(y_q - y_{p1})\left[\tan^{-1}\frac{(x_q - x_{p1})}{(y_q - y_{p1})} - \tan^{-1}\frac{(x_q - x_{p2})}{(y_q - y_{p1})}\right]\end{array}\right] \tag{2}$$

Likewise (2) may be simplified to:-

$$\mathrm{B}_y(x_q, y_q) = \frac{+J_p\mu 0}{4\pi}\left[\begin{array}{l}(y_q - y_{p2})\ln\left[\frac{(y_q - y_{p2})^2 + (x_q - x_{p2})^2}{(y_q - y_{p2})^2 + (x_q - x_{p1})^2}\right] \\ + 2(x_q - x_{p2})\left[\tan^{-1}\frac{(y_q - y_{p2})}{(x_q - x_{p2})} - \tan^{-1}\frac{(y_q - y_{p1})}{(x_q - x_{p2})}\right] \\ + (y_q - y_{p1})\ln\left[\frac{(y_q - y_{p1})^2 + (x_q - x_{p1})^2}{(y_q - y_{p1})^2 + (y_q - y_{p2})^2}\right] \\ + 2(x_q - x_{p1})\left[\tan^{-1}\frac{(y_q - y_{p1})}{(x_q - x_{p1})} - \tan^{-1}\frac{(y_q - y_{p2})}{(x_q - x_{p1})}\right]\end{array}\right] \tag{3}$$

The force density $\bar{f}(x_q, y_q)$ acting on the point (x_q, y_q) may be simply computed from the expression:

$$\bar{f}(x_q, y_q) = J_q\overline{u}_z \times \left\{B_x(x_q, y_q)\overline{u}_x + B_y(x_q, y_q)\overline{u}_y\right\} \tag{4}$$

The overall force per unit length $\overline{F_l}(Q)$ acting on the busbar enclosing the point (x_q, y_q) may be computed from:

$$\overline{F_l}(Q) = \int_{x_{q1}}^{x_{q2}}\int_{y_{q1}}^{y_{q2}}\bar{f}(x_q, y_q)dy_q dx_q \tag{5}$$

By superposition, the overall force per unit length acting on a busbar may be computed due to all surrounding busbars.

ANALYSIS AND SAMPLE SIMULATION OF 3-PULSE RECTIFIER

In order to calculate the forces between busbars due to harmonic currents, a simple non-linear load circuit of 3-pulse rectifier is chosen. The circuit topology is shown in Fig. 3. Many simulation cases have been done at different firing angles. This paper presents the values at α=120°. The supply currents, taken from the experimental model, are used in local force density calculation over one cycle in order to know the effect of harmonics on local force densities. To control the load voltage, the circuit uses three common cathode thyristor arrangement [10].

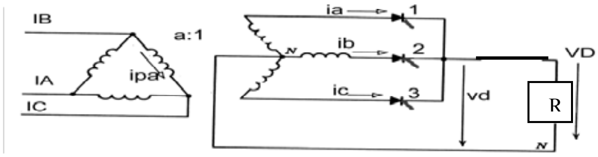

Fig. 3. Three-phase half-wave rectifier.

Thus, three-pulse rectifier generates all the harmonics except the triplen harmonics. Using Fourier analysis, the spectrum will be as shown in Fig. 4.

A. Experimental Results

The experimental model consists of a drive circuit that controls the firing angle needed to trigger the thyristor and a power circuit. The power circuit shown in Fig. 3 consists of transformer delta/star 220/50 volt is connected to a variable resistance load 320 ohm adjusted to 102 ohm. The load voltage V_D and the distorted secondary phase current i_a at α=120° are shown in Fig. 5 and Fig. 6.

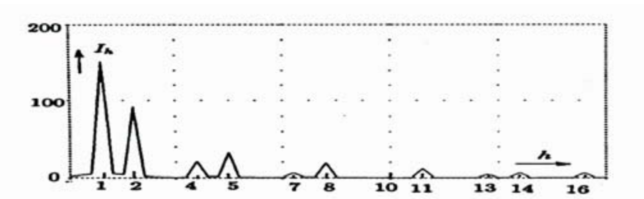

Fig. 4. Current frequency spectrum.

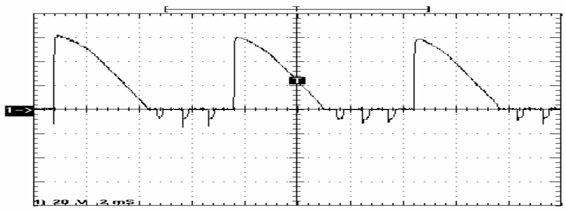

Fig. 5. Load voltage VD at α=120°.

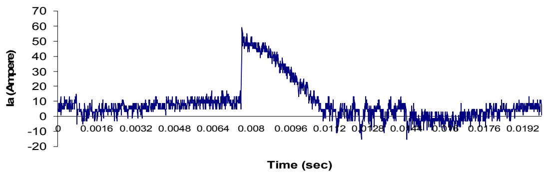

Fig. 6. Secondary phase current ia at α=120^{o}.

The other phase currents waveforms i_b, i_c will be similer to i_a , but shifted by 120°, 240° dergree. The primary phase currents will have the same waveforms but divided over the transformer turns ratio.

Forces between bus bars connected to this experimental non-linear load will be calculated in the next section with the help of the line currents calculated form this experimental model.

OVERALL FORCES AND LOCAL FORCE DENSITIES DUE TO 3-PULSE RECTIFIER

The harmonic currents are taken from the experimental model discussed in the previous section. One cycle is taken in the calculations, by dividing it to 37 parts as there are 37 commutation point . The overall force and local force densities are calculated in every part of the 37 parts.

The busbars structure description of harmonic simulation case is shown in TABLE I. The local force densities distribution along X and Y direction in every busbar at certain time instants are shown in the following figures.

TABLE 1 HARMONIC SIMULATION CASE

Busbar structure description	Quantity
Busbar width	0.02 m
Busbar height	0.06 m
Inter-busbar spacing	0.05 m

1) From time = 0 to 0.00222 second

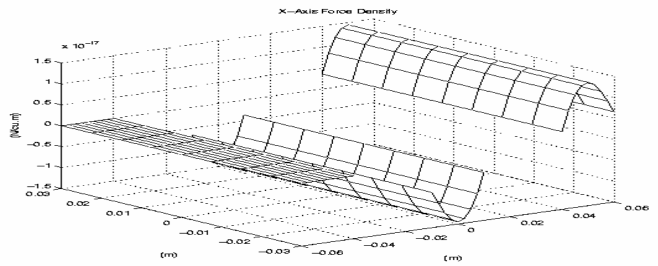

Fig. 7. Force density distribution along the x-direction in every busbar from time=0 to 0.00222 second.

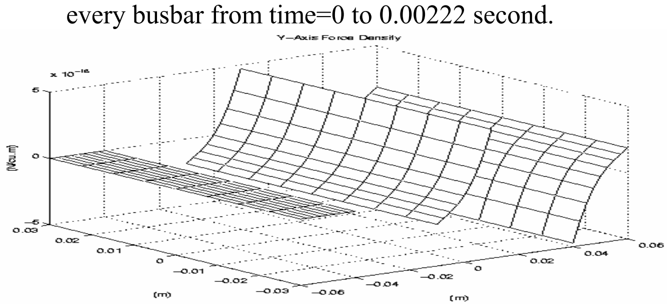

Fig. 8. Force density distribution along the Y-direction in every busbar from time=0 to 0.00222 second.

2) From time = 0.00277 to 0.01055 second

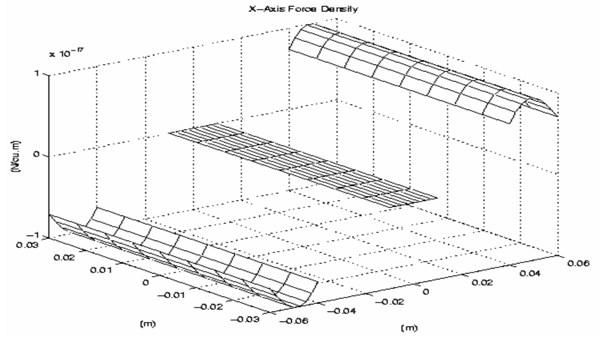

Fig. 9. Force density distribution along the x-direction in every Busbar From time = 0.00277 to 0.01055 second.

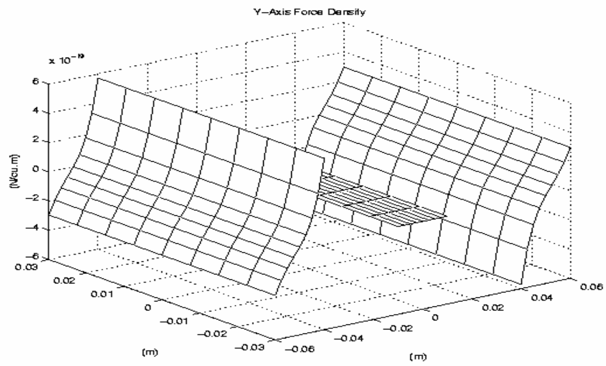

Fig. 10. Force density distribution along the Y-direction in every Busbar From time = 0.00277 to 0.01055 second.

3) At time = 0.0111 second

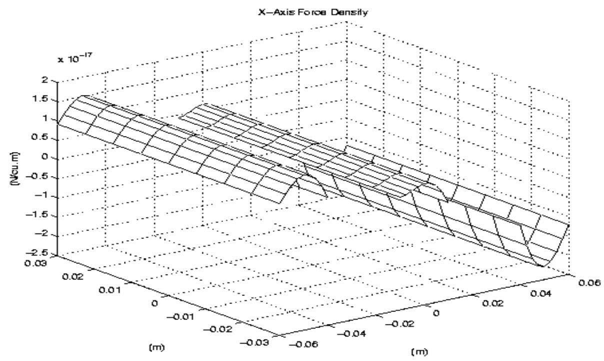

Fig. 11. Force density distribution along the x-direction in every Busbar at time =0.0111 second

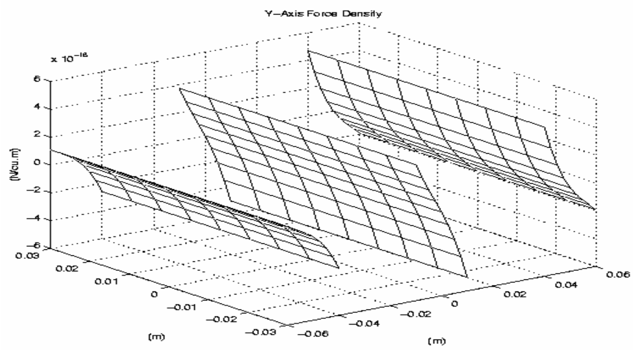

Fig. 12. Force density distribution along the Y-direction in every Busbar at time =0.0111 second

4) From time = 0.01166 to 0.0166 second

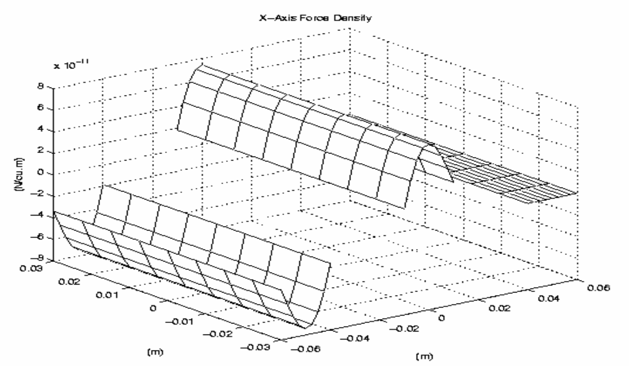

Fig. 13. Force density distribution along the x-direction in each Busbar from time =0.01166 to 0.0166 second

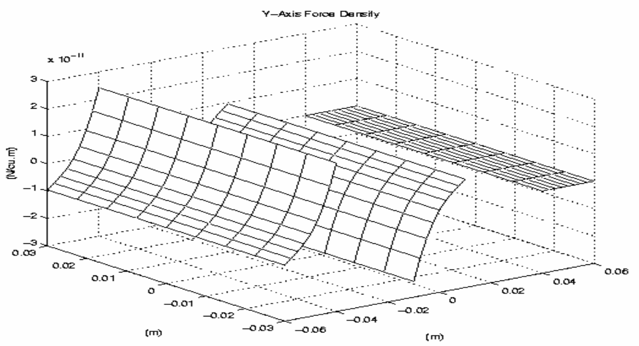

Fig. 14. Force density distribution along the Y-direction in each Busbar from time =0.01166 to 0.0166 second

5) From time = 0.01722 to 0.02 second

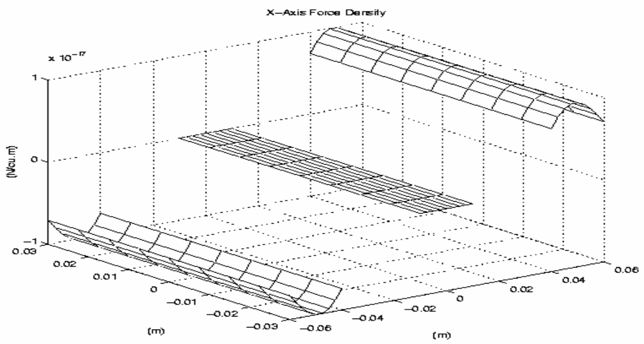

Fig. 15. Force density distribution along the x-direction in each Busbar from time =0.01722 to 0.02 second

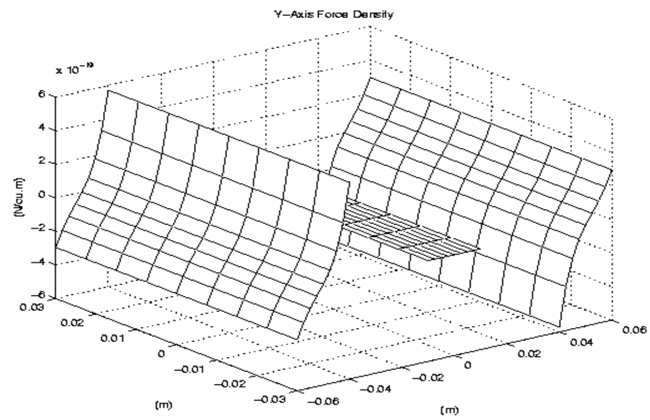

Fig. 16. Force density distribution along the Y-direction in each Busbar from time =0.01722 to 0.02 second

CONCLUSIONS

It can be seen that the developed expressions of local force density may be used to examine the local force densities acting on a certain busbar. The developed expressions may also be very useful in computing the overall forces applied on the three phase busbars. These forces can be taken as a guideline while selecting the suitable busbars support structure.

The forces in the presence of harmonics causes excess vibrational stresses on the busbars as the changes of currents in the presence of harmonics are more than its absence. These stresses may cause rupture of the insulating supports and permanent busbar bending. Thus, the presence of harmonic currents resulting from non-linear load must be considered while calculating the forces between busbars.

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