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Analysis on How to Locate the Maximum Line Voltage to Hull in Steady State on the Vector Diagram Onboard Vessels

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Abstract : Power distribution onboard vessel is typically configured as ungrounded system due to the ability to continuously supply electric power even when an earth fault occurs. The impedance connections between 3 phase power lines and hull cause the line-to-hull voltages to become unstable and increased in case the impedances are unbalanced, bringing the situation susceptible to electric shock and deterioration of insulation material. Also the line-to-hull voltage can reach to a certain maximum value in the steady state depending on the distributed capacitances and grounding resistances between lines and hull. This study suggests how to find and calculate the maximum line-to-hull voltage in view of magnitude and phase angle based on the vector diagram.

Key words : Ungrounded power system, Line to ground voltage, neutral point, distributed capacitance

1. Introduction

Onboard vessels, ungrounded power distribution systems are usually adopted to avoid the risk of service failure at the time of an earth fault. But the fault brings uprising line to hull voltages on the healthy phases and more stressful situation to their insulation materials [1-3] and various studies have been conducted for fault protection and detection [4-5].

In case of an earth fault, the deformed feature of line-to-hull voltages on the vector diagram can be reasonably described by positioning the neutral point which varies according to the insulation resistances and distributed capacitance between electric wires and hull [6-7]. One doubt about line-to-hull voltages on the real systems is that the measurement at healthy phase sometimes indicates high voltages even surpassing the line-to-line voltage under a certain condition of earth fault which is not in resonant or intermittent grounding. The detailed cause of this surpassing high voltage in the steady state has not been known so far even if it is important when considering the ungrounded power distribution systems. But it is expected that the reason of this feature could be analyzed and disclosed if the neutral point at this indication on the vector diagram is found.

This study focuses on how to get the neutral point which brings the peak line-to-hull voltage based on the loci patterns of neutral points. And its peak value and phase angle from calculation will be compared with the measured results at a real distribution system for experiment.

2. Neutral point on vector diagram

2.1 Vector of neutral point

Figure 1 is a schematic circuit to describe the situation of the power distribution lines onboard a

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ship which are linked by insulation resistances R_R, R_S, R_T for each phase and distributed capacitances C between power lines and hull. Here, $\dot{V}_R$, $\dot{V}_S$ and $\dot{V}_T$ are phase voltages and 'N' indicates the neutral point at healthy condition. If a power line is grounded, the neutral point 'N' is moved to 'n' by $\dot{V}_{nN}$ as shown in Figure 2.

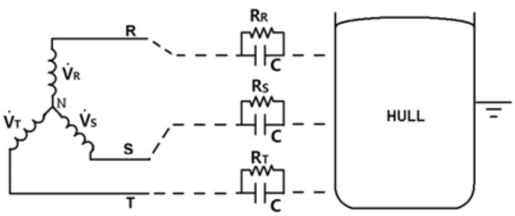

Figure 1: Schematic circuit of power lines to hull

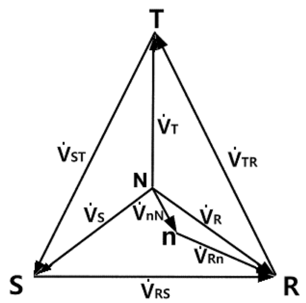

Figure 2: Neutral point 'n' on the vector diagram

To know the position of neutral point 'n' on the vector diagram, we can use the equation (1), (2) and (3) based on the relation of the schematic circuit.

$$\dot{V}_R = \dot{V}_{Rn} + \dot{V}_{nN} \tag{1}$$

$$\dot{V}_S = \dot{V}_{Sn} + \dot{V}_{nN} \tag{2}$$

$$\dot{V}_T = \dot{V}_{Tn} + \dot{V}_{nN} \tag{3}$$

The line-to-hull voltages $\dot{V}_{Rn}$, $\dot{V}_{Sn}$ $\dot{V}_{Tn}$ of the above corresponds to the product of the leakage current to the ground and the impedances through which they flows at each phase, and we get equation (4), (5) and (6).

$$\dot{V}_{Rn} = \dot{I}_R \dot{Z}_R \tag{4}$$

$$\dot{V}_{Sn} = \dot{I}_S \dot{Z}_S \tag{5}$$

$$\dot{V}_{Tn} = \dot{I}_T \dot{Z}_T \tag{6}$$

Where, $\dot{I}_R$, $\dot{I}_S$ and $\dot{I}_T$ are the leakage current to hull at each phase. And $\dot{Z}_R, \dot{Z}_S, \dot{Z}_T$ are impedances at 3 phase lines consisting of insulation resistance and capacitance C as follows.

$$\dot{Z}_R = \frac{R_R(1 - j\omega R_R C)}{1 + \omega^2 R_R^2 C^2} \tag{7}$$

$$\dot{Z}_S = \frac{R_R(1 - j\omega R_S C)}{1 + \omega^2 R_S^2 C^2} \tag{8}$$

$$\dot{Z}_T = \frac{R_T(1 - j\omega R_T C)}{1 + \omega^2 R_T^2 C^2} \tag{9}$$

In addition, the relation of leakage currents to hull shall be as equation (10).

$$\dot{I}_R + \dot{I}_S + \dot{I}_T = 0 \tag{10}$$

From the above equations, we get following equation as a function of impedances and $\dot{V}_{nN}$.

$$\frac{\dot{V}_R - \dot{V}_{nN}}{\dot{Z}_R} + \frac{\dot{V}_S - \dot{V}_{nN}}{\dot{Z}_S} + \frac{\dot{V}_T - \dot{V}_{nN}}{\dot{Z}_T} = 0 \tag{11}$$

Then, $\dot{V}_{nN}$ becomes equation (12) which allows the neutral point to be plotted on the vector diagram.

$$\dot{V}_{nN} = \frac{\dot{Z}_R \dot{Z}_S \dot{V}_T + \dot{Z}_S \dot{Z}_T \dot{V}_R + \dot{Z}_T \dot{Z}_R \dot{V}_S}{\dot{Z}_R \dot{Z}_S + \dot{Z}_S \dot{Z}_T + \dot{Z}_T \dot{Z}_R} \tag{12}$$

2.2 neutral points on the complex plane

For plotting the neutral point, the result of equation (12) needs to be described by a complex variable as shown in equation (13).

$$\dot{V}_{nN} = \frac{\alpha_2 + j\beta_2}{\alpha_1 + j\beta_1} = V_X + jV_Y \tag{13}$$

Before obtaining the real part V_X and the imaginary part V_Y of $\dot{V}_{nN}$, it is necessary that the coefficients α_1, β_1 of the denominator part of equation (12) and α_2, β_2 of the numerator part are acquired from the data of impedances and the source voltages.

If these 4 coefficients are calculated from a given power system, then V_X and V_Y can be expressed as equation (14) and (15).

$$V_X = \frac{V_P}{2}\,\frac{\alpha_1\alpha_2 + \beta_1\beta_2}{\alpha_1^{\,2} + \beta_1^{\,2}} \tag{14}$$

$$V_Y = \frac{V_P}{2}\,\frac{\alpha_1\beta_2 - \alpha_2\beta_1}{\alpha_1^{\,2} + \beta_1^{\,2}} \tag{15}$$

Where, $V_P = |\dot{V}_R| = |\dot{V}_S| = |\dot{V}_T|$, and V_P is the phase voltage.

If R_R, R_S, R_T and C are given at a distribution system, each coefficient becomes as follows.

$$\alpha_1 = R_{RS}k_{RS}k_T + R_{ST}k_{ST}k_R + R_{TR}k_{TR}k_S \tag{16}$$

$$\beta_1 = -k_1\{R_{RS}R_{R+S}k_T + R_{ST}R_{S+T}k_R + R_{RS}R_{R+S}k_T\} \tag{17}$$

$$\begin{aligned}\alpha_2 = {} & 2R_{RS}k_Rk_T - R_{TR}\{k_{RS} + \sqrt{3}\,k_1R_{T+R}\}k_S \\ & - R_{RS}\{k_{RS} - \sqrt{3}\,k_1R_{R+S}\}k_T\end{aligned} \tag{18}$$

$$\begin{aligned}\beta_2 = k_1\{ & -2R_{ST}R_{S+T}k_R + R_{TR}(R_{T+R} - \frac{\sqrt{3}}{k_1}k_{TR})k_R \\ & + R_{RS}(R_{R+S} + \frac{\sqrt{3}}{k_1}k_{RS} - \sqrt{3}\,k_1R_{R+S})k_T\ \}\end{aligned} \tag{19}$$

Where, ω is angular frequency with unit of [rad/s], and

$k_1 = \omega C$, $k_2 = \omega^2 C^2$,

$R_{RS} = R_R R_S$, $R_{ST} = R_S R_T$, $R_{TR} = R_T R_R$,

$k_R = 1 + k_2 R_R^{\,2}$, $k_S = 1 + k_2 R_S^{\,2}$, $k_T = 1 + k_2 R_T^{\,2}$

$k_{RS} = 1 - k_2 R_{RS}$, $k_{ST} = 1 - k_2 R_{ST}$,

$k_{TR} = 1 - k_2 R_{TR}$

3. Loci of neutral points

Figure 3 is the loci of $\dot{V}_{nN}$ on the complex plane under the condition the insulation resistance at R phase only is being lowered gradually from 1.0[MΩ] to 0[Ω] with constant R_S and R_T of 1.0 [MΩ]. The lines of $\dot{V}_{RN}$, $\dot{V}_{SN}$ and $\dot{V}_{TN}$ represents the voltages to hull at healthy condition.

The loci A, B, C, D and E are at cases where the capacitance C for the distributed capacitance of power line system is given as 0[μF], 0.001[μF], 0.01[μF], 0.1[μF] and 1.0[μF], respectively. When capacitance is zero, the locus shows it follows the real axis in the form of straight line.

In addition, it appears that the more the capacitance C increases, the more the locus tends to have the shape of half circle. Here we know that curve D and E overlap each other showing same curves. This indicates that if the capacitance is higher than 0.1[μF] with the insulation condition given previously, the eventual curves become an apparent half circle with diameter V_{RN} equal to the phase voltage of a 3 phase power system. The general results from various cases show the domain of neutral points is always limited inside the boundary of this half circle. It explains that the maximum line-to-hull voltage can be acquired only when the locus moves along the way of the half circle.

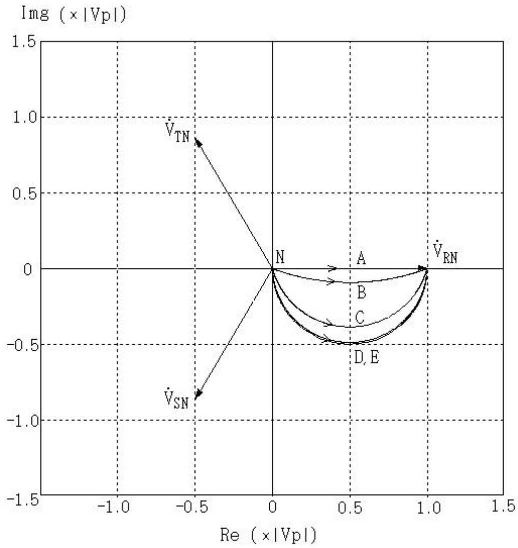

Figure 3: Loci of neutral points at 5 cases of C (0 [μF], 0.001[μF], 0.01[μF], 0.1[μF] and 1.0[μF])

4. Locating maximum line to hull voltage

4.1 Critical neutral point

If the insulation resistance R_R is lowered and the capacitance C is quite big, the locus becomes the Fig.4 where the curve of half circle shows the diameter corresponding to the phase voltage of 3 phase power lines in length. Here $\dot{V}_{Tn}$, the voltage between the T phase line and neutral point 'n' which is called the voltage to hull at T phase goes higher than the phase voltage V_P in the whole path. In Figure 4, $\dot{V}_{TS}$ indicates $\dot{V}_{Tn}$ at the time when the R phase line has been grounded completely with the voltage magnitude corresponding to the line to line voltage V_L of 3 phase power system. Likewise, $\dot{V}_{TL}$ represents $\dot{V}_{Tn}$ just when the magnitude of $\dot{V}_{Tn}$ equals V_L and n_c is the neutral point of this case. On the way passing through the locus, neutral points before the critical neutral point n_c causes V_{Tn} to be less than V_L. From the point n_c, there are two curves described as 1 and 2 before reaching the same point (1, j0) corresponding to completely grounded condition. Curve 2 is a drawn line for reference which makes the length V_{Tn} equal to V_L. From the relation of curves 1 and 2, it is obvious that the real V_{Tn} becomes greater than V_L if V_{Tn} is between 2 lines of $\dot{V}_{TL}$ and $\dot{V}_{TS}$. The position of n_c which makes V_{Tn} same as V_L can be decided by Equation (20) and (21) based on the geometry relation.

$$(V_X + \frac{V_P}{2})^2 + (V_Y + \frac{\sqrt{3}}{2} V_P)^2 = (\sqrt{3} V_P)^2 \quad (20)$$

$$V_Y = \sqrt{V_X (V_P - V_X)} \quad (21)$$

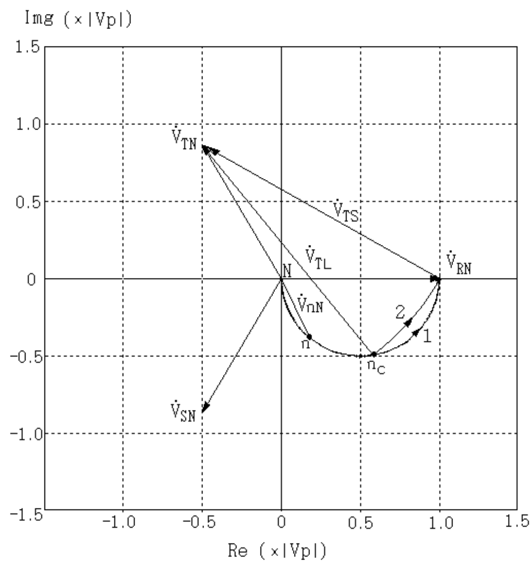

Figure 4: Critical neutral point n_c on the plane

Then, the real part V_{XC} and the imaginary part V_{YC} of n_c are acquired as follows.

$$V_{XC} = \frac{4}{7} V_P \quad (22)$$

$$V_{YC} = \frac{2\sqrt{3}}{7} V_P \quad (23)$$

4.2 Maximum line to hull voltage

The movement of neutral point 'n' from the origin to a point on the locus in Figure 4 causes V_{Tn} to vary in the range from phase voltage to a certain high voltage, and V_{Tn} experiences once becoming a peak value while R phase line is gradually grounded to 0[Ω]. If the peak V_{Tn} is denoted as V_{TM}, it shall locate between 2 lines of $\dot{V}_{TL}$ and $\dot{V}_{TS}$ as shown in Figure 5.

The length of V_{Tn} in Figure 5 can be expressed by equation (24) as a function of variable V_X and V_Y.

$$V_{Tn} = \sqrt{(V_X + \frac{V_P}{2})^2 + (V_Y + \frac{\sqrt{3}}{2} V_P)^2} \tag{24}$$

And as V_Y is a function of V_X by equation (21), we get equation (25) for the magnitude of $\dot{V}_{Tn}$ which include only one variable V_X.

$$V_{Tn} = [\, V_P{}^2 + V_P \sqrt{3\, V_X\, (V_P - V_X)} + 2 V_P V_X \,]^{\frac{1}{2}} \tag{25}$$

Then, V_{TM}, the peak V_{Tn}, can be found when the derivative of equation (26) becomes zero.

$$\frac{d\,[V_{Tn}]}{dV_X} = 0 \tag{26}$$

If n_m is denoted as the neutral point which bring V_{TM} and its real part and the imaginary part are defined as respectively V_{XM} and V_{YM}, the result is shown as follows.

$$V_{XM} = 0.75\, V_P \tag{27}$$

$$V_{YM} = \frac{\sqrt{3}}{4} V_P \tag{28}$$

Figure 5 describes how V_{TM} and n_m are located on the vector diagram in relation with $\dot{V}_{TL}$ and $\dot{V}_{TS}$.

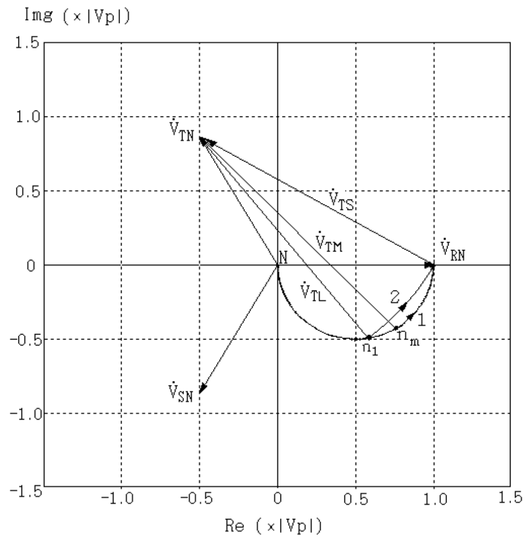

Figure 5: Maximum line to hull voltage

And if V_{XM} is given to equation (29) instead of V_X, V_{TM} is acquired as follows.

$$V_{TM} = \frac{\sqrt{13}}{2} V_P \approx 1.8 V_P \tag{29}$$

This result indicates that V_{TM} becomes 1.8 times the phase voltage and even exceeds V_L called line-to-line voltage as much as 4% higher than that in the steady state. The phase angle ϕ_M at V_{TM} from the origin becomes equation (30).

$$\phi_M = \tan^{-1} \frac{j V_{YM}}{V_{XM}} = -\frac{\pi}{6} [rad] \tag{30}$$

5. Experiments and discussion

5.1 Experimental procedures

Figure 6 is the configuration for experiments where 3 volt meters V_1, V_2 and V_3 were prepared for measuring V_{Rn}, V_{Sn} and V_{Tn}. The base metal in the schematic diagram which is a kind of power distribution console was used for the ground purpose instead of ship hull. And three miler condensers of $0.1[\mu F]$ were connected for C_R, C_S and C_T between each power lines and the base metal for the effect of distributed capacitance. Here, the line to line voltage V_L of the 3 phase power line is 220[V] and the phase voltage V_P becomes 127[V]. For R_S and R_T, two solid resistors of 1[MΩ] were used and one rheostat was connected for R_R to adjust R phase insulation resistance from 1.0[MΩ] to 0 [Ω]. To find how the line-to-hull voltage at each phase are affected according to earth condition at one phase, R_R was decreased gradually by the rheostat and the indication of V_1, V_2 and V_3 were measured and recorded. Here, five measuring cases denoted as 'a', 'b', 'c', 'd', 'e', 'f' and 'g' were chosen to compare the measuring values with calculated values. The 'a' case was selected to compare both results at healthy condition where V_X of neutral point is zero.

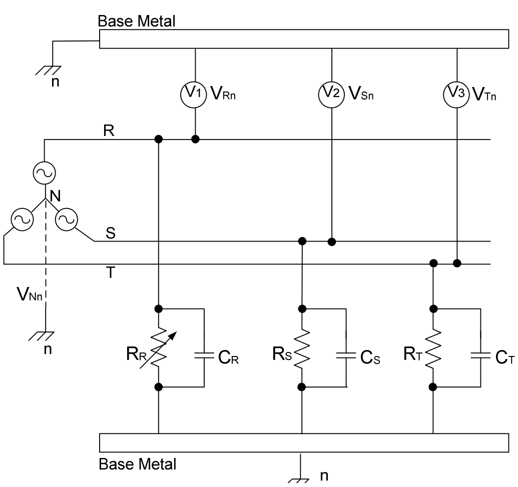

Figure 6: Schematic diagram for experiment

The value V_X at 'b' case is when it is $0.25 V_P$, and 'c' case is for $V_X = 0.5 V_P$. The 'd' case was chosen where V_{Tn} becomes V_{TL}. And at 'e' case, the values of V_{TM} can be checked. The 'e' case is when V_X is $0.75 V_P$ and case 'g' corresponds to the completely grounded condition.

5.2 Results of measurement

From equation (13) and (24), the value of V_{Tn} is acquired by calculation if R_R, R_S, R_T and C is given. Here, it is possible to adjust the rheostat to cause the indication of volt meter V_3 to become the same value as the calculated V_{Tn} at each case of 'a', 'b', 'c', 'd', 'e', 'f' and 'g'. After the rheostat was adjusted to match the indication of V_3 with the calculated V_{Tn}, then the rheostat resistances were measured as $\overline{R}_R$. And the indication of volt meter V_1, V_2 and V_3 were also recorded as $\overline{V}_{Rn}$, $\overline{V}_{Sn}$ and $\overline{V}_{Tn}$ as described in Table 1.

Table 1 Values of calculation and measurement ($C_R = C_S = C_T = 0.1[\mu F]$)

	R_R, R_S, R_T $\overline{R}_R$, $\overline{R}_S$, $\overline{R}_T$	V_{Rn} $\overline{V}_{Rn}$	V_{Sn} $\overline{V}_{Sn}$	V_{Tn} $\overline{V}_{Tn}$	V_X, V_Y
a	1[MΩ],1[MΩ],1[MΩ] 1[MΩ],1[MΩ],1[MΩ]	127.0 127.3	127.0 127.7	127.0 127.2	0, 0
b	15.32[kΩ],1[MΩ],1[MΩ] 14.40[kΩ],1[MΩ],1[MΩ]	109.2 108.7	110.8 111.2	189.0 190.1	31.7, -53.3
c	8.76[kΩ],1[MΩ],1[MΩ] 8.62[kΩ],1[MΩ],1[MΩ]	88.6 89.1	135.8 135.4	213.7 214.2	63.5 -61.8
d	7.56[kΩ],1[MΩ],1[MΩ] 7.72[kΩ],1[MΩ],1[MΩ]	81.8 82.3	144.6 144.1	218.7 219.2	72.6, -61.2
e	4.99[Ω],1[MΩ],1[MΩ] 5.2[Ω],1[MΩ],1[MΩ]	63.1 63.8	168.2 167.1	228.7 229.8	95.3, -53.3
f	3.23[kΩ],1[MΩ],1[MΩ] 3.15[kΩ],1[MΩ],1[MΩ]	43.3 42.5	188.0 187.6	229.4 229.6	111.1, -40.3
g	0[kΩ],1[MΩ],1[MΩ] 0[kΩ],1[MΩ],1[MΩ]	0 0	220.0 221.2	220.0 220.6	127.0, 0

The result of Table 1 shows that the measuring values at experiments indicate nearly the same as the calculated values each other in all cases from ‘a’ to ‘g’. On the right column of Table 1, the calculated values of V_X and V_Y have been added to show the position of neutral points for each case.

The neutral points at Table 1 are also described in Figure 7 where the neutral point marked ‘c’ is the lowest point on the locus way. At this point, it was supposed that V_X and V_Y should be same if the locus is true half circle. But, it appears that V_Y is less than V_X indicating that the locus is slightly not a true half circle maybe because the capacitances of connected condensers are not enough to become a true half circle.

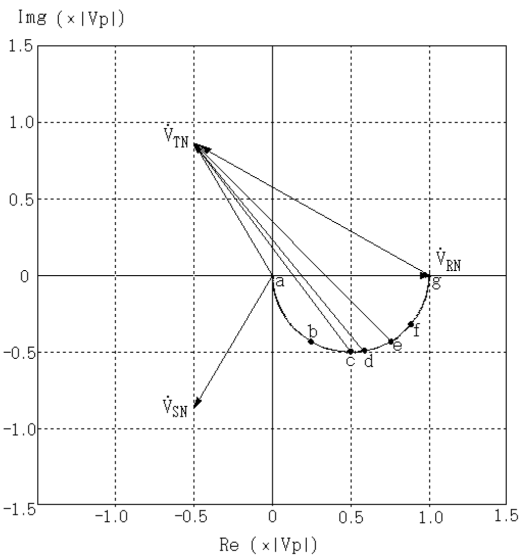

Figure 7: Neutral points corresponding to Table 1

The maximum line-to-hull voltage was expected at case ‘e’ but in calculation values it is found at case ‘f’. The reason of this deviation could be explained from the fact that the locus is slight not a true half circle. But in both measuring values and calculated value, the maximum line-to-hull voltages indicates the value is 4% higher than V_L the line-to-line voltage.

6. Conclusions

This paper suggested how to find the maximum line-to-hull voltage in steady state rather than at transient condition when an earth fault occurs at power distribution system. The neutral point having this max line-to-hull voltage could be found on the path which corresponds to the locus of a half circle while a power line is being grounded for analysis. The result showed that the line-to-hull voltage can increase up to 1.8 times the phase voltage which even exceeds line-to-line voltage as much as 4% higher than that in steady state based on the vector diagram.

But the position of maximum line-to-hull voltage in the calculated values was found to be slightly deviated from the expected one. The reason of this result is considered to be because the locus was not a true half circle under the chosen data.

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