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Investigation of Parallel Generator Unit-Connection effects on Third Harmonic Stator Earth Fault Protection

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Abstract

Third harmonic protection is one of the methods used for preventing damage to generator stator winding due to earth fault. Its effects have been investigated for single generator unit connection. However, there is a dearth of information on its effects on parallel generator unit connection which is a more practical situation in generating stations. In this work, the effect of parallel generator unit-connection on third harmonic earth fault protection is investigated.

Ordinary non-linear algebraic equations obtained from non-fault and earth fault circuit models of two generators connected in parallel using Kirchhoff's voltage and current laws for different load conditions were solved using Cramer's rule. Simulation of the models for earth fault at stator neutral and terminal were performed for no-load, light load and full load using MATLAB/SIMULINK. The value of third harmonic voltage at stator neutral and terminal were estimated for the different load conditions. Third Harmonic Voltage (THV) at neutral and terminals of the parallel generators for no-load, light load and full load conditions were 115.8 V and 60 V, 66.8 V and 34.7 V, 231.6 V and 120.1 V respectively for non-fault condition. With an earth fault at the neutral of generator one, THV at its neutral and terminal became 0 V and 160 V, 0 V and 92.5 V, 0 V and 320 V for no-load, light load and full load conditions respectively while generator two has 140.4 V and 56.5 V, 75.5 V and 23.5 V, 280.8 V and 113 V at neutral and terminal respectively. In conclusion, for an earth fault on one generator of a parallel unit connected pair, values of third harmonic voltage at its neutral and terminal agrees with that of a single unit-connected generator. As a result, third harmonic protection will operate effectively if applied to a parallel generator unit connection.

Keywords: Synchronous, generator, MATLAB/SIMULINK, Kirchhoff, Fault, Simulation.

Introduction

Synchronous generators are either unit-connected or bus connected. Unit-connected generators are associated with a dedicated step-up transformer. It could be single or multiple generators-in-parallel connected to a transformer. In a generator bus connection, the generator is connected to a bus to serve consumer loads which could be domestic or industrial. The generator is not associated with a dedicated transformer.

Ground faults are a major cause of stator winding insulation breakdown of synchronous generators. Zero sequence voltage relays used for winding protection against single phase ground faults on unit connected generators cannot cover 100% of stator winding as a result of the dead zone at or near the generator neutral [1].

Considering investigation results of the ground fault processes and analysis of failures of some unit-connected generators, it is reported that the ground fault protection of the generator stator windings should detect ground faults at any point of the winding including the generator neutral [2]. A combination of zero sequence voltage relays and relays tuned to the third harmonic voltage provide 100% protection for the generator stator winding [3].

Third harmonic voltage is produced by all generators and is present in the two ends of the stator windingbut in different magnitude. The magnitude is dependent on the design of the machine [4]. It also varies according to the load level, the measurement point and the fault location along the winding. Its normal values are between 1% and 6% of the nominal generator voltage, in the case of non-faulted windings [4]

The character of third harmonic voltage present at the generator terminals when a ground fault

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occurs near the neutral end of the stator winding is that its value at that point of the stator decreases towards zero but towards the terminal point of the stator, it increases towards maximum. When a ground fault occurs close to the generator terminal, the character is the reverse. [5]

The protection scheme excited by third harmonic voltage is influenced by generator terminal connections [6]. Implementation of the 100% protection therefore requires a compatibility check on the particular generator terminal connection with the third harmonic strategy to be applied on the generator.

Unit and bus connections are common methods of generator terminal connection. Unit connected generators can be single generator or multiple generators unit connection. Investigation of the influence of parallel unit-connected generators of the second order on the range and character of third harmonic voltage at the terminals of the generators' and consequently the third harmonic protection is the focus of this paper.

Materials and methods

The parallel unit-connected generator of the second order can be operated in either of two modes: single generator or parallel operation modes. In studying the influence of the parallel connection on third harmonic protection, the two modes of generator operation are modeled for the non-fault and fault conditions of the stator winding.

The stator winding capacitance to ground and the capacitances of the elements at the generator terminals are modelled as single capacitors to ground [4]. The resistances at the neutral points of the generators are also modelled as single resistors. A typical parallel unit-connected generator of the second order is shown in Figure 1 where:

C_{gA}, C_{gB} = Stator winding capacitance to ground of generators A & B
C_{xA}, C_{xB} = Total capacitance to ground of all elements connected to generator terminals.
R_{nA}, R_{nB} = Neutral resistance for generators A & B.
C_t = Step-up transformer capacitance to ground

Non-fault and fault models of the single and parallel generator operating modes are implemented to study the variation of third harmonic voltage at the generator terminals when the generator is running normally and when a ground fault occurs in the stator winding of one of the generators. The circuit implementation is done using MATLAB / SIMULINK.

Third harmonic voltage across the terminal and neutral of the generators under normal operating condition is evaluated from the non-fault model. When a fault occurs along the stator, this voltage changes. Variation of this voltage magnitude for different values of fault resistance on the stator is evaluated from the fault model.

Third harmonic voltage present at stator neutral and terminal is influenced by generator active power[7] therefore the effect of generator loading for full load, light load and no-load conditions is studied.

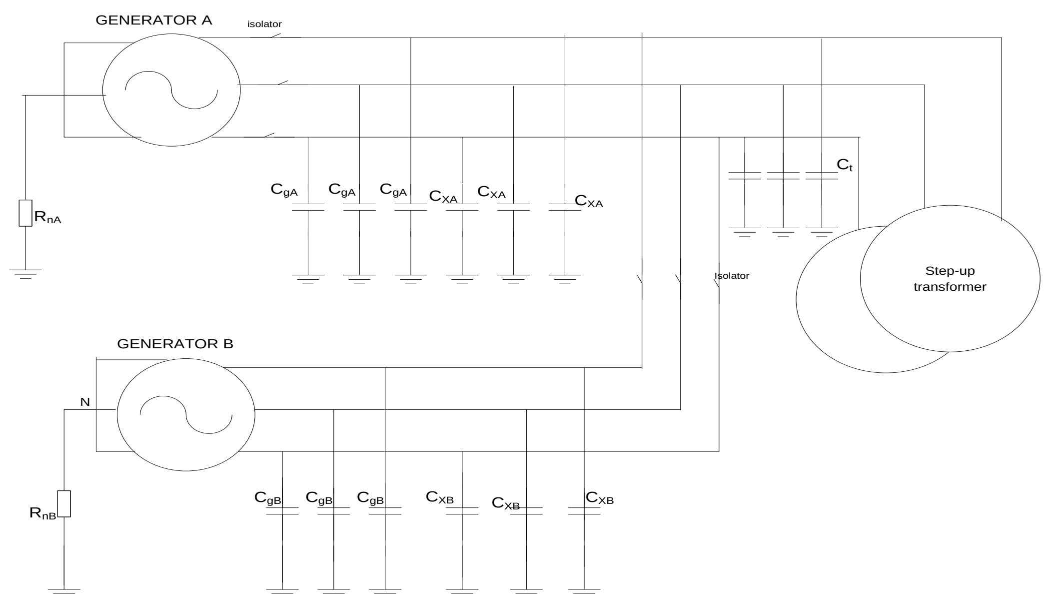

Figure 1: Typical two generators in-parallel

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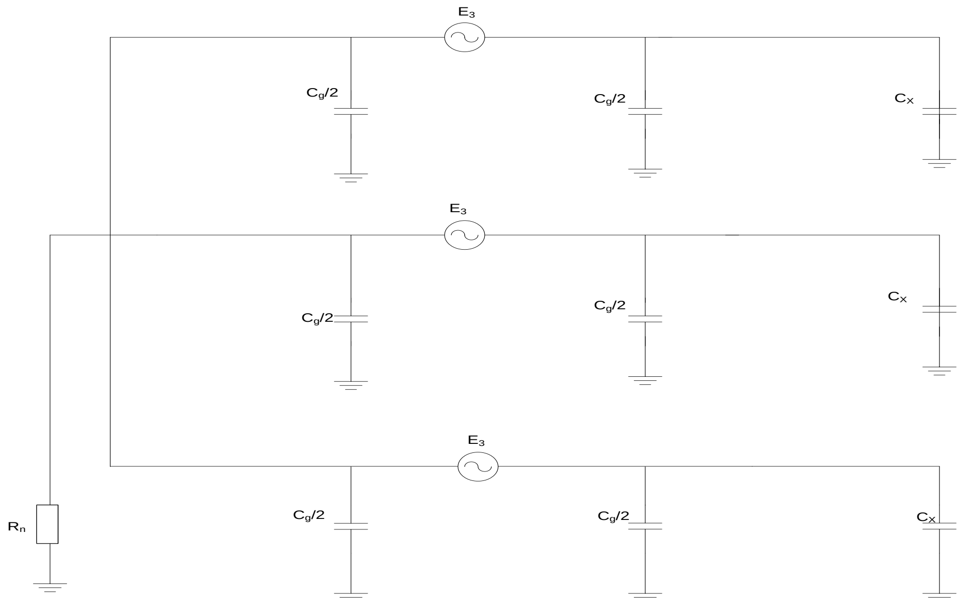

Figure 2a: Single generator non-fault model

The non-fault and fault models and their equivalent circuits are shown in Figures 2, 3 and 4 where:

E_{31}, E_{32} = Third harmonic voltage produced in generators 1 & 2.
C_g = Phase capacitance to ground of the stator winding.
C_{x1}, C_{x2} = Total capacitance of elements connected to generators 1 & 2.
R_{n1}, R_{n2} = Neutral resistance of generators 1 & 2 .
R_f = Fault resistance
α = Fault location along stator from neutral to terminal.

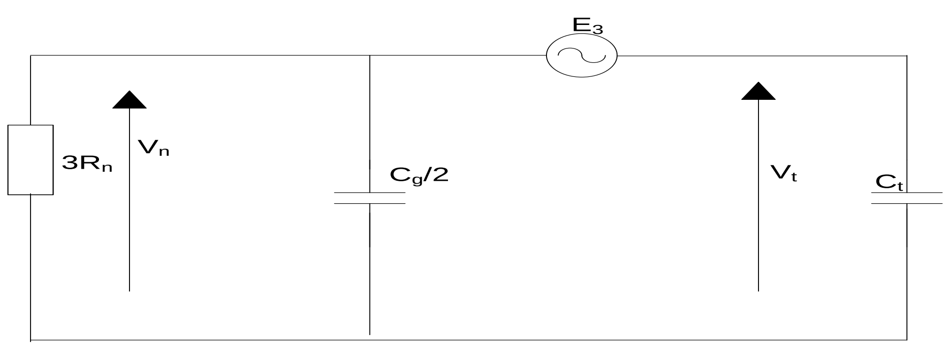

Figure 2b: Simplified third harmonic voltage circuit for single generator

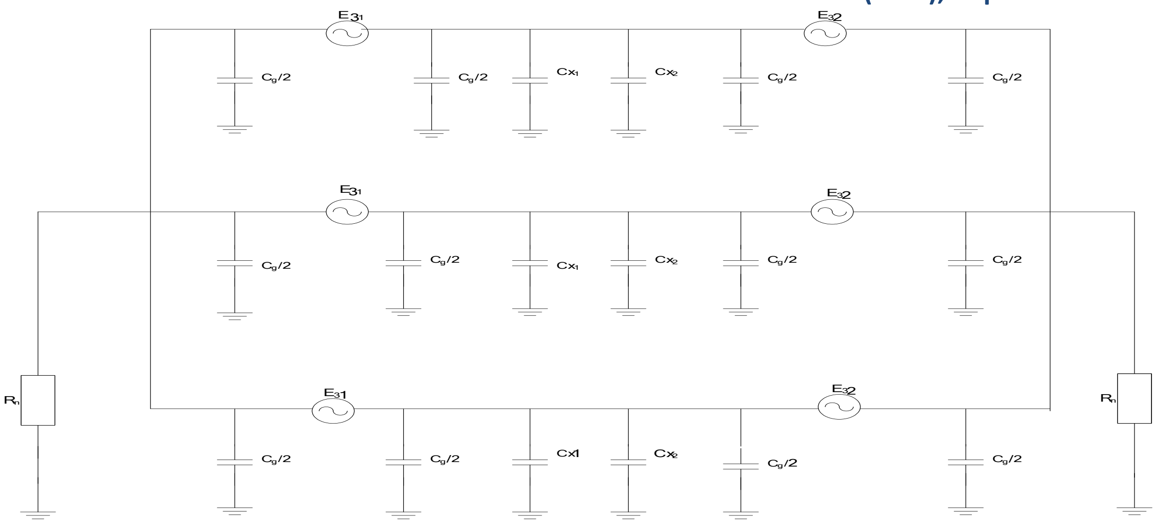

Figure 3: Parallel operationnon-fault model

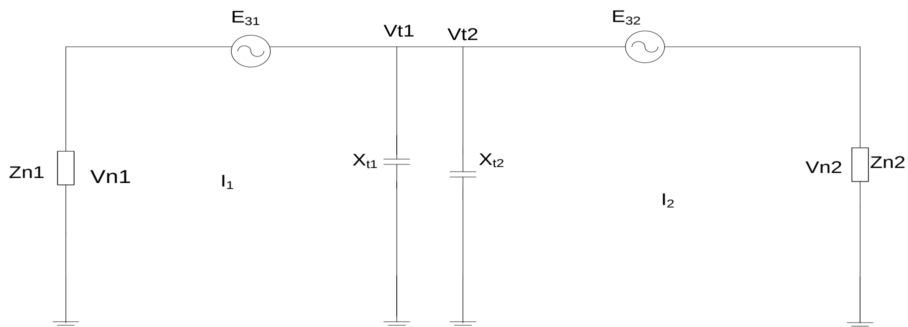

Figure 4: Simplified non-fault zero sequence voltage circuit.

Validation of the non-fault models

The SIMULINK Validation of the non-fault models is done to verify that the circuit models implemented to study the phenomenon of interest is built appropriately. The validation is by comparison of results obtained from analysis of the circuit model and computer simulation of the model built using MATLAB/SIMULINK.

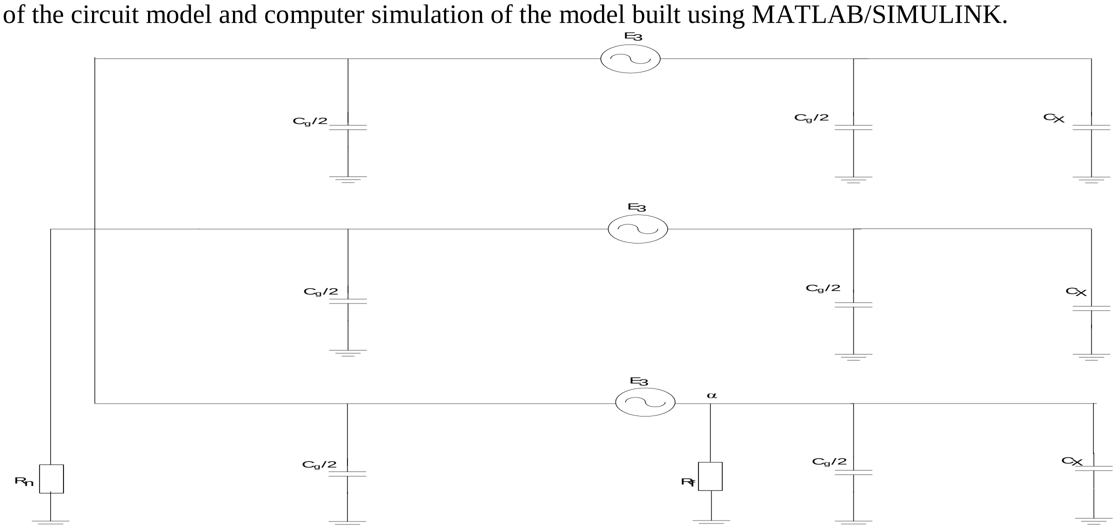

Figure 5: Single generator fault model

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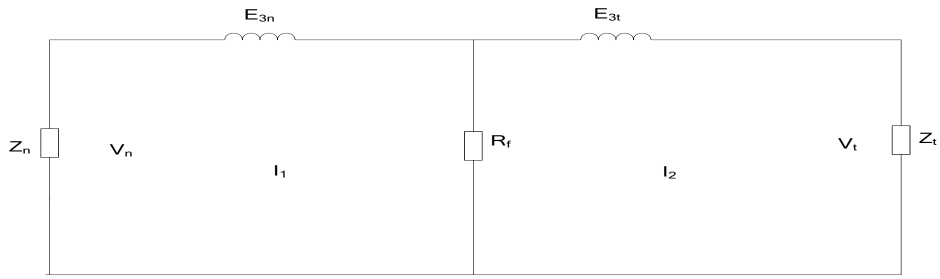

Figure 6: Third harmonic voltage circuit

Generator-Transformer unit Parameter

Generator rated voltage: 16KV
Rated Power: 80MW
Frequency: 50Hz
Stator winding capacitance: 0.6µF
Grounding resistance: $\frac{16}{\sqrt{3}}$, , 10Amps, 925Ω
Circuit breaker capacitance: 0.1µF
Step-up transformer Capacitance: 0.1µF; Bus capacitance: 0.05µF
Step-up transformer power: 184MVA

Total third harmonic voltage produced in the generator can be calculated or measured at the stator terminals.It is calculated as 1% of rated voltage [4] However, as a result of non-availability of measurement devices, total third harmonic voltages were obtained by calculation. The calculation is based on1% of rated voltage. Result obtained is shown in Table 1.

No-load
1% of 16KV = 160V
Full-load = 100% of No-load
Full load = 320V
Light load = 1% of phase to neutral voltage
Phase to neutral voltage = $\frac{16000}{1.73}$= 9248V
1% of phase to neutral voltage = 92.48 ≈ 92.5V

Table 1: Total third harmonic voltage

Load Level	E_3 (V)	% Phase Neutral Voltage	% E_3 to no-load
No-load	160	1.73	100
Full load	320	3.46	200
Light load (30% of Full load)	92.5	1	57

Parallel operation non-fault validation

For the parallel operation, the circuit model of figure 3 is connected back to back for implementation in SIMULINK to obtain the neutral and terminal voltages. Using the circuit of Figure 4, the voltages across the neutral and generator terminals are also calculated as follows using mesh analysis:

$$E_{31} = I_1(Z_{n1} + X_{t1}) - I_2X_t \tag{1}$$
$$E_{32} = I_1X_{t2} - I_2(X_{t2} - Z_{n2}) \tag{2}$$
$$\begin{bmatrix} E_{31} \\ E_{32} \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \begin{bmatrix} Z_{n1} + X_{t1} & -X_{t2} \\ X_{t2} & X_{t2} - Z_{n2} \end{bmatrix} \tag{3}$$
$$\begin{bmatrix} 92.5 \\ 92.5 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \begin{bmatrix} 1718.4 - j2482.9 & j1135.4 \\ -j1135.4 & 1718.4 - j212 \end{bmatrix} \tag{4}$$

Where;
$E_{31} = E_{32}$ = 92.5; $Z_{n1} + X_t = (1718.4 - j2482.9)$; $X_{t2} = -j1135.4$;
$X_{t2} - Z_{n2} = 1718.4 - j212.5$; Δ_0 = 6647926.46;

$$I_1 = \frac{\Delta_1}{\Delta_0} \tag{5}$$

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$I_2 = \frac{\Delta_2}{\Delta_0}$ (6)

On light load condition

$\Delta_1 = \begin{bmatrix} j1135.4 & 92.5 \\ 1718.4 - j212.5 & 92.5 \end{bmatrix}$ (7)

$\Delta_1 = 202017.9$; $I_1 = 0.0303A$

$\Delta_2 = \begin{bmatrix} 1718.4 - j212.5 & 92.5 \\ -j1135.4 & 92.5 \end{bmatrix}$ (8)

$\Delta_2 = 202017.9$; $I_2 = 0.0303A$;

$V_{n1} = V_{n2} = I_1 Z_{n1}$ (9)

$$V_{n1} = V_{n2} = 66.3$$

$V_{t1} = V_{t2} = I_1 X_{t1}$ (10)

$$V_{t1} = V_{t2} = 34.5$$

Calculated values of neutral and terminal voltage of the generators under non-fault conditions for generator loading are shown in Table 2. The simulation was implemented using circuit model of Figure 3. A comparison of the calculated and simulated results show a maximum error less than 1% as shown in Table 4 for all load conditions.

Table 2A: Neutral Voltage

Load	V_{n1} Calculated	V_{n2}	V_{n1} Simulated	V_{n2}	Error (%)
FL	229.5	229.5	231.6	231.6	9
LL	66.3	66.3	66.8	66.8	0.75
NL	114.7	114.7	115.8	115.8	0.95

Table 2B: Terminal Voltage

Load	V_{n1}	V_{n2}	V_{n1}	V_{n2}	Error (%)
	Calculated		Simulated		
FL	119.4	119.4	120.1	120.1	0.58
LL	34.5	34.5	34.7	34.7	0.58
NL	59.6	59.6	60.0	60.0	0.67

For Tables 2A & 2B, FL = full load, LL = light load, NL= no-load

Single generator non-fault validation

For the circuit model of Figure 4b, application of mesh analysis yields voltages across the neutral and generator terminals as follows:

$X_t = Xc_t = \frac{1}{2\pi f C_t}$ (11)

$C_t = [\frac{1}{2} C_g + C_x]$ (12)

$X_t = \frac{1}{\pi f c_t}$ (13)

$X_t = \frac{1}{2x\,3.14\;x150x(0.636x10^{-6})}$ (14)

$X_t = -J1669.1\Omega$

$Z_n = (X_n)//(3R_n)$ (15)

$X_n = \frac{1}{2\pi f C_n}$ (16)

$X_n = \frac{1}{6.28 \times 150 \times (0.3 \times 10^{-6})}$

$X_n = -3538.6\Omega$

$Z_n = \frac{X_n \times (3Rn)}{X_n + 3\,R_n}$ (17)

$R_n = 925\Omega$; $3Rn = 2775\Omega$

Subtituting for R_n in equation (17) gives

$Z_n = 1718.4 - j1347.5\Omega$

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The voltage at generator teminal and neutral (V_t) and (V_n) respectively is easily obtained using voltage divider.

V_t = 76.9V, V_n = 100.6V

For the three load conditions, the table of voltages across stator neutral and terminal are shown in Table 3. It can be seen that the values of terminal and neutral voltage obtained by analysis of the circuit model and computer simulation are close. Calculated error from comparison of both results is a maximum of 0.13%. This validates the model implemented in SIMULINK.

Table 3: Single generator calculated and simulated values

Load	V_{n1}	V_{n2}	Error (%)	V_{n1}	V_{n2}	Error (%)
	Calculated			Simulated		
FL	201.2	201.4	0.9	153.8	153.7	06
LL	58.1	58.2	0.75	44.4	44.4	0
NL	100.6	110.7	0.95	76.9	76.8	0.13

Parallel operation fault model analysis

Figure 7 shows the fault model of a parallel generator. Figure 8 illustrates the simplified fault zero sequence voltage circuit. The value of voltage at terminal and neutral of both generators when a fault occurs on one of the pair can be evaluated from the analysis of Figure 8 as shown.

$$E_{3n} = I_1(R_f - Z_1) - I_2R_f \quad (18)$$

$$E_{3t} = I_1R_f + I_2(X_{t1} - R_f) + I_3X_{t1} \quad (19)$$

$$E_{32} = I_2X_{t2} - I_3(X_{t2} - Z_{n2}) \quad (20)$$

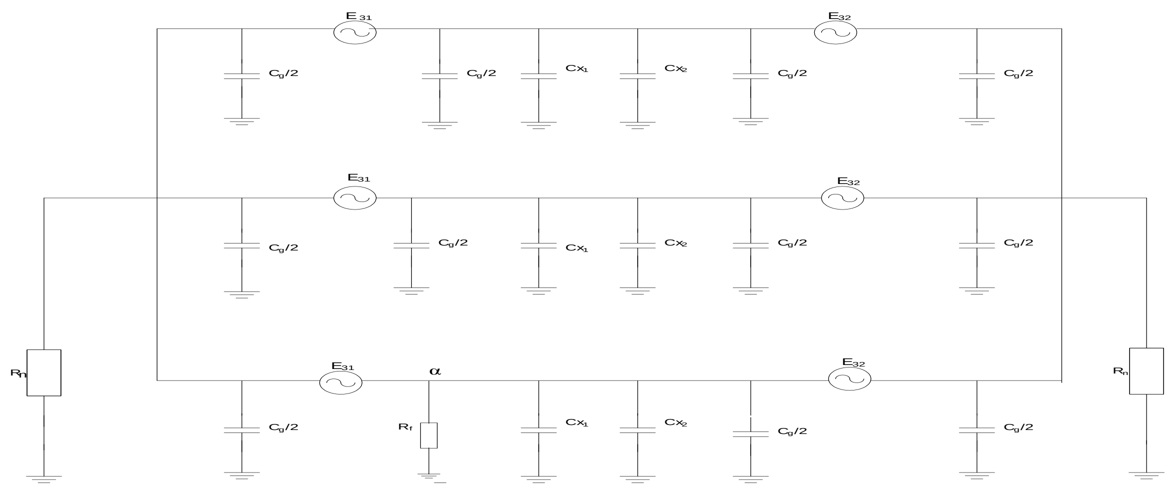

Figure 7: Parallel Generator Fault Model

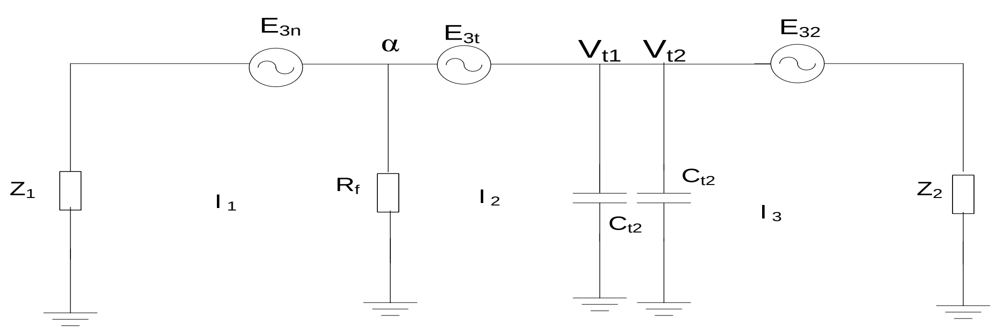

Figure 8: Simplified fault zero sequence voltage circuit

The three sets of equation (18) to (20) in matrix form

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$$\begin{bmatrix} E_{3n} \\ E_{3t} \\ E_{32} \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \begin{bmatrix} R_f - Z_{n1} & -R_f & 0 \\ R_f & X_{t1} - R_f & X_{t1} \\ 0 & X_{t2} & X_{t2} - Z_{n2} \end{bmatrix} \quad (21)$$

Applying Cramer's rule to equation (21) matrix,

$$I_1 = \frac{\Delta_1}{\Delta_0};\ I_2 = \frac{\Delta_2}{\Delta_0};\ I_3 = \frac{\Delta_3}{\Delta_0} \quad (22)$$

$$V_{n1} = I_1 Z_{n1} \quad (23)$$

$$V_{n2} = I_3 Z_{n2} \quad (24)$$

$$V_{t1} = (I_2 + I_3) X_{t1} \quad (25)$$

$$V_{t2} = (I_3 + I_2) X_{t2} \quad (26)$$

The voltage at terminal and neutral of the generators under different fault conditions can be calculated using equations (23) to (26)

Results and discussion

Non-fault simulation

From the results obtained from the simulation of non-fault models, it is observed that voltage at neutral in a single generator mode is lower compared with parallel operation. (Tables 2 &3)At the terminal however, the reverse is the case. This is representative of the influence of the additional capacitances at the terminals of the generators in the parallel operation.

It is also seen that in the parallel operation of the generators, the neutral and terminal voltage with unequal loading is different from the values obtained when the generators are equally loaded. With unequal loading combination (light/full load) of the generators, the neutral third harmonic voltage for light loading is lower than the value obtained when both generators are lightly loaded (Figures 9a & 9b). The reverse is however the case for a full loading condition where the neutral third harmonic voltage for the unequal loading combination is higher than the value obtained from the full load equal loading combination.

Also, the voltage at the terminals of the generators in the unequal loading combination is equal for both generators whereas for equal loading combination, the voltage at the stator terminals varies according to the loading level. This is representative of the effect of loading combination on the third harmonic voltage present at the stator neutral in normal operation.

Fault simulation

The graph illustrating full load condition of the single generator operation mode for a fault condition is shown in Figure 10. The character of third harmonic voltage for the single generator mode for the different load conditions is identical. Two conditions of generator loading were studied for the parallel operation (Figure 11).

Condition 1: When the two generators are running on equal load for light load, no-load and full load modes of operation.

Condition 2: When one generator is running on light load while the other is on full load. For condition 2, parallel operation when the light loaded generator is on fault and when the full loaded generator is on fault were studied.

Condition 1: Equal loading

It is seen that when a ground fault occurs on one generator of the pair, the character of neutral and terminal voltage of this generator is similar to a single unit-connected generator. The neutral voltage decreased from 231.6V at neutral for non-fault condition (Table 2) towards zero (depending on and limited by the fault resistance) but increased at the terminal. However, the character of third harmonic voltage across the un-faulted generator of the pair differs.

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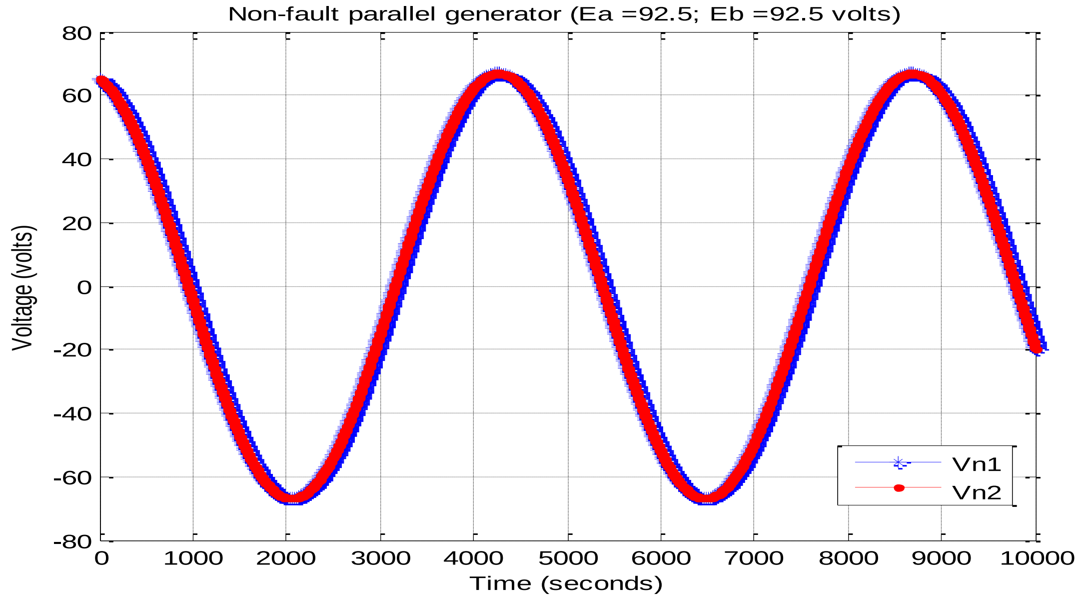

Figure 9a: Equal generator loading neutralvoltage

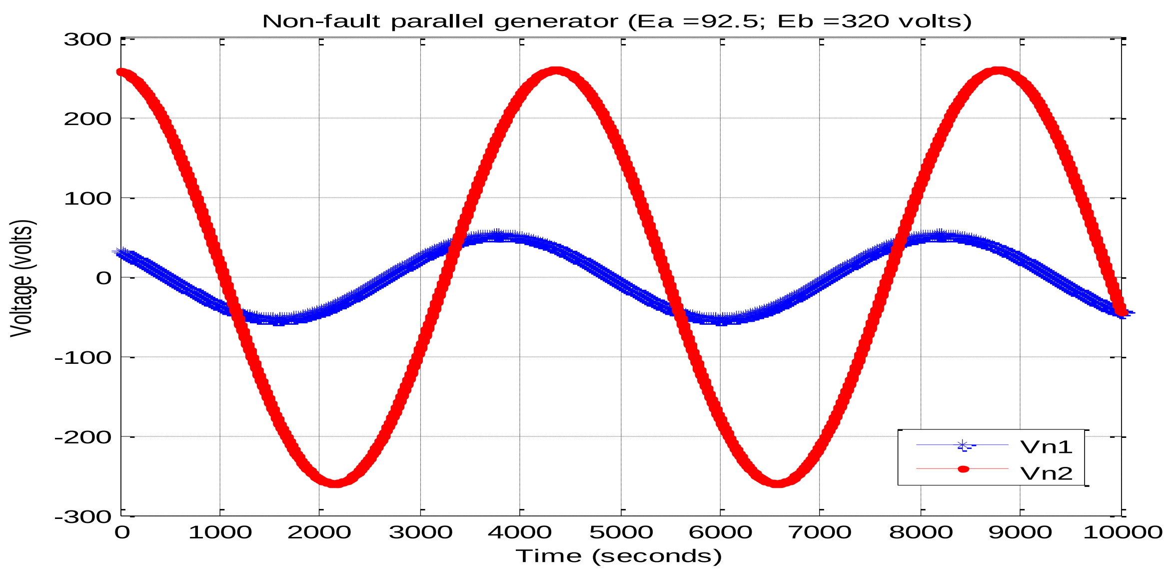

Figure 9b: Unequal generator Light/full loading neutral voltage

With a fault on one generator, the voltage at the neutral of the other generator increases beyond the non-fault level (Figure 11b). Hence, the character of third harmonic voltage at neutral of un-faulted generator is similar to voltage at terminal of a single unit-connected generator in a fault condition. The difference being that this neutral voltage is fairly constant across the stator length from stator neutral to terminal points. It is also constant for all values of fault resistance. The variance is less than 1% for different values of fault resistance. This character applies for all load conditions considered.

The range and character of voltage at the neutral of the un-faulted generator presents an additional protection strategy that can be explored for equally loaded parallel connected generators of the order under study. Usually, in a single generator unit-connection, a ground fault at the neutral cause voltage at the terminal to increase to maximum. An over-voltage relay at the terminal can be used to protect the stator against ground fault at the neutral.

In the parallel arrangement considered, since voltage at neutral of un-faulted generator increased for a fault on the other generator of the pair, an overvoltage protection can be applied at neutral of un-faulted generator to protect the other generator in the event of a ground fault on this generator. The character of third harmonic voltage at the

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terminal of the un-faulted generator in the parallel arrangement under study also presents a strategy to protect the faulted generator.

It is seen that for a fault at the neutral of one generator, the terminal voltage of the other generator decreased to a value below the non-fault value (Figure 12). This slight decrease in voltage can be used to excite under-voltage relays to initiate tripping of the faulted generator.

From the results obtained, two additional protection strategies can be explored on parallel connected generators of the order under study for third harmonic stator ground fault protection when the generators are equally loaded. These are under-voltage strategy at the terminal of the un-faulted generator and over-voltage strategy at the neutral of the un-faulted generator.

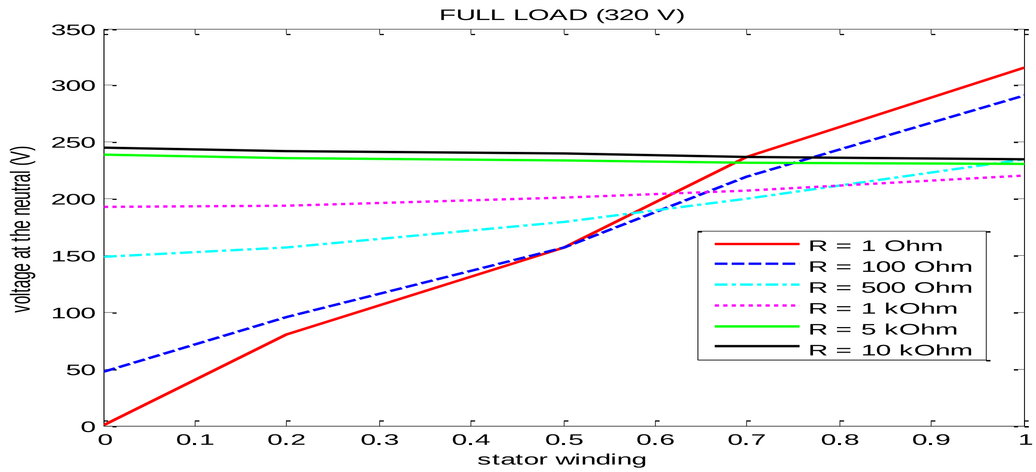

Figure 10: Single generator fault full load

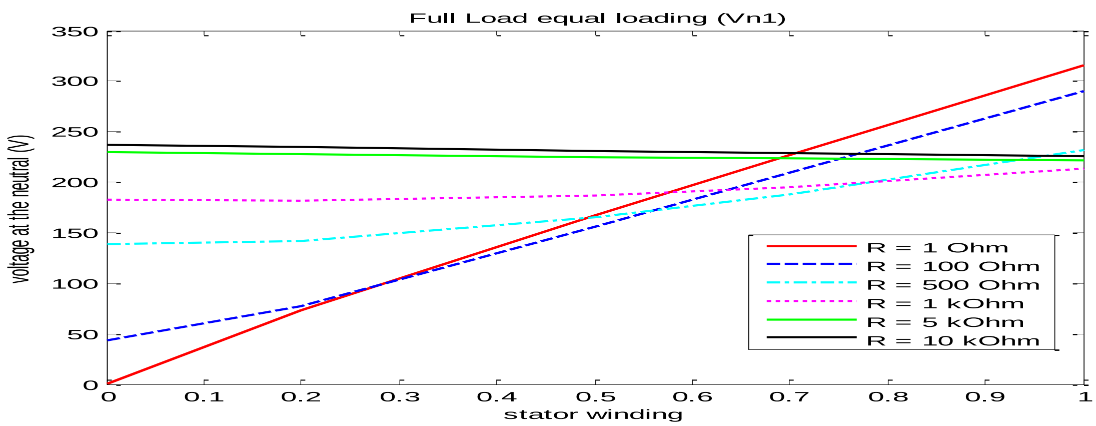

Figure 11a: Parallel operation neutral voltage on full load (generator A)

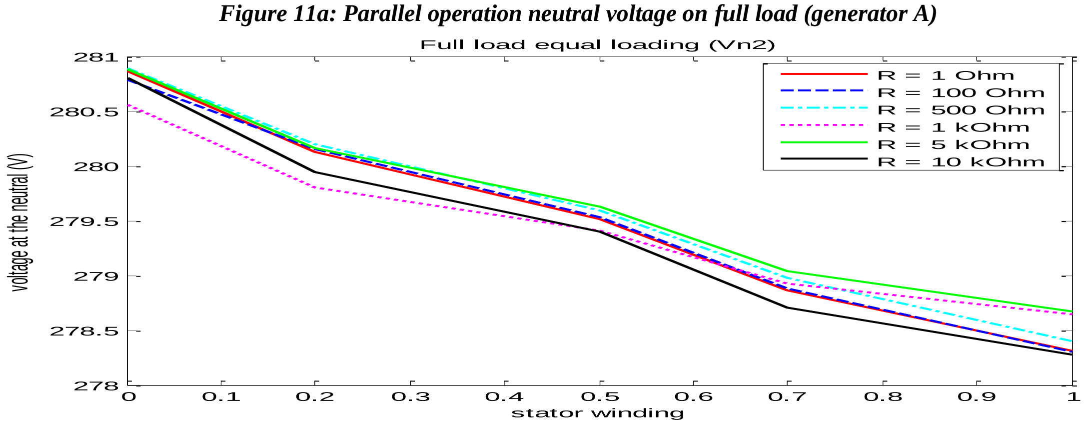

Figure 11b: Parallel operation neutral voltage on full load (generator B)

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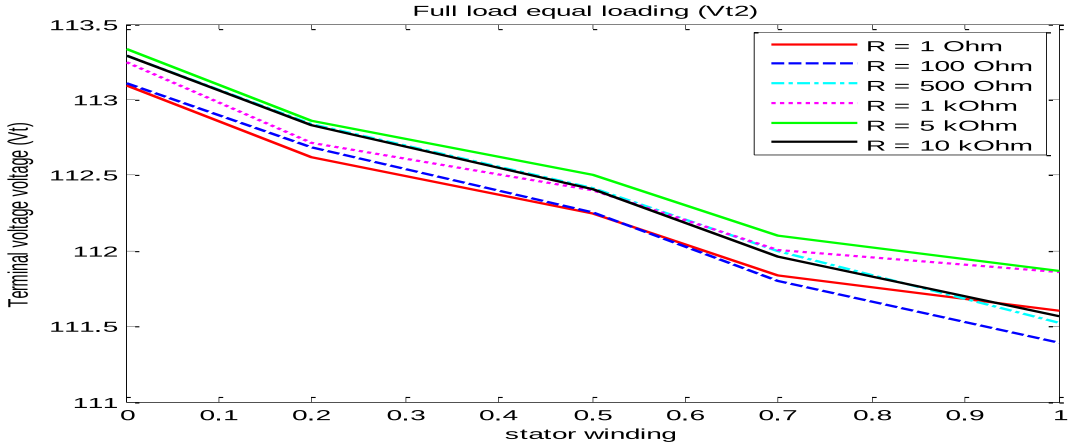

Figure 12: Parallel operation terminal voltage on full load (generator B)

Condition 2:Un-equal loading

For condition 2 of unequal loading, two loading patterns were considered.

i). When a ground fault has occurred one generator (labelled A) lightly loaded while the other generator (labelled B) is fully load.

ii). When a ground fault has occurred one generator (labelled A) fully load while the other generator (labelled B) is lightly load. For this two load patterns, the range and character of third harmonic voltage at neutral and terminal of the generators differ.

i). Loading pattern 1 - (Light/Full load)

When the lightly loaded generator is on fault, the voltage at the neutral and terminal of the fully loaded un-faulted generator increased (Figure 13). This is contrary to the result obtained when the two generators are running on full load and one of the pair is faulted where neutral voltage increased and terminal voltage decreased. This implies that the under-voltage protection at the terminal of the unfaulted generator identified for the equal loading condition cannot be applied.

ii). Loading pattern 2 - (Full/light load)

When the fully loaded generator is on fault, the character of voltage at the neutral and terminal of the lightly loaded un-faulted generator is identical to the case when both generators are equally lightly loaded and one of the pair is faulted. Neutral voltage increased while terminal voltage decreased. (Figure14). The slight increase and decrease can be used to excite protective relays. The two implementation strategies for third harmonic protection identified above are therefore applicable to this mode of operation and loading pattern.

This difference in the character of third harmonic voltage at the neutral and terminal of the generators for loading patterns 1 and 2 above reflects load influence on the character of the third harmonic voltage in a fault condition for parallel unit-connected generators of the order under study (Figures 13&14). It also implies multiple settings for the protective elements in parallel connected generators for different load conditions.

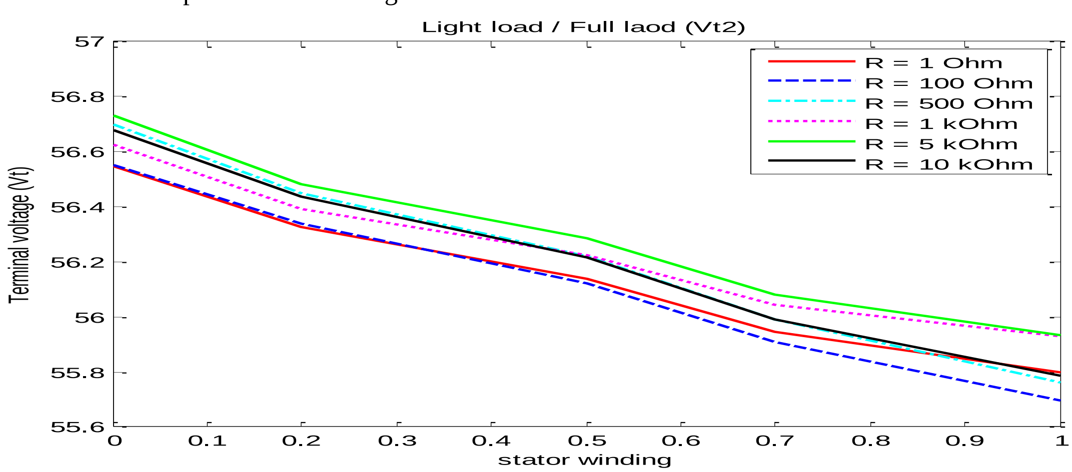

Figure 13a: Terminal voltage VS stator length (generator B)

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Considering the unequal loading modes of patterns 1 and 2, it is seen from the results that when the lightly loaded generator is on fault, it is able to detect a lower fault resistance than when the fully loaded generator is on fault. The fault detection range of the parallel unit-connection is therefore dependent on the loading combination of the generators at the instant of the ground fault.

The character of third harmonic voltage for all the modes of generator operation considered in this work shows clearly the influence of a parallel unit-connected generator of the second order on third harmonic protection system

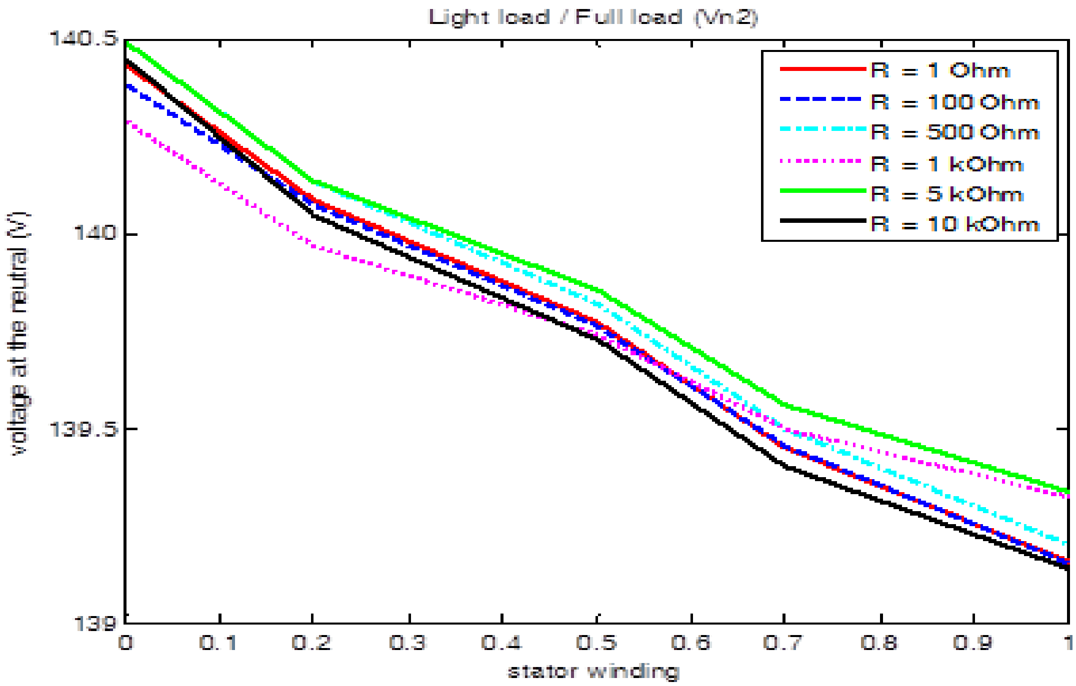

Figure 13b: Generator B neutral voltage VS stator length (parallel operation unequal loading)

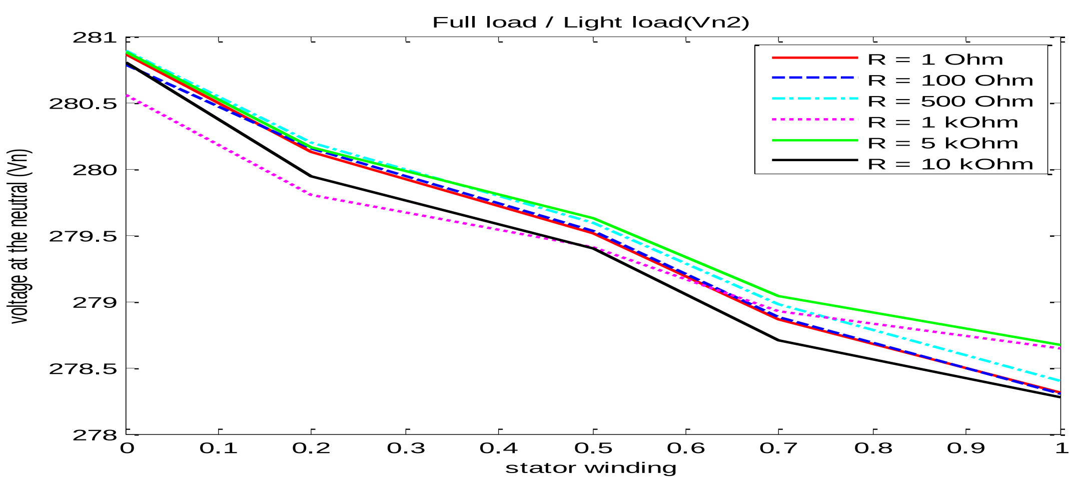

Figure 14a: Neutral voltage VS stator length

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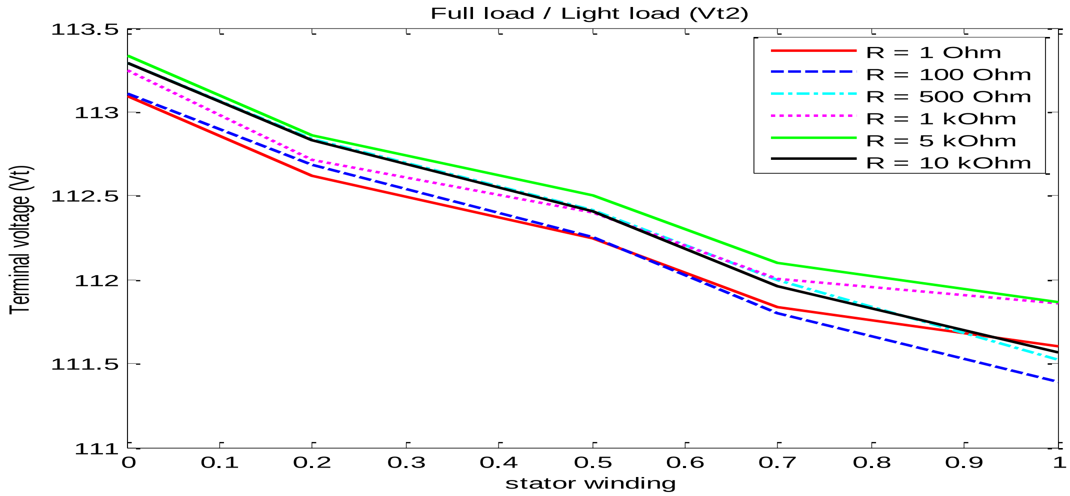

Figure 14b: Terminal voltage VS stator length

Conclusion

In non-fault modes, voltage at the neutral in the single generator operation is lower than the parallel operation. At the terminal however, the reverse is the case. The range and character of third harmonic voltage at the generator terminals of the faulted generators for a single generator and parallel operation modes are identical. The range and character of third harmonic voltage at the generator terminals of the unfaulted generator in the parallel operation however differ from the faulted generators for both operation modes.

The range and character of third harmonic voltage at the neutral and terminal of an unfaulted generator in the parallel operation also differ for equal and different unequal loading combinations. The combination loading of the unequally loaded generator is seen to influence the character of third harmonic voltage at neutral and terminal of the generators.

For parallel connected generators of the order studied, two additional strategies for implementing the third harmonic protection is proposed.These are an under-voltage strategy at the terminal of the un-faulted generator and over-voltage strategy at the neutral of the un-faulted generator. The variation in range and character of third voltage at the neutral and terminals of the generators in the parallel arrangement for different load conditions implies multiple settings for the protective elements. Appropriate alarm trip logic will be required to avoid mal-operation of the protection system as a result of the multiple settings.

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