Investigation of the Voltage Balance Scheme to Protect the Generator from Ground Fault

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Abstract

The article discusses the features of protecting the stator winding of the generator from ground faults using the voltage balance method. It has been established that this scheme can be used regardless of the generator load regime. The regimes of closing the generator winding to the ground for the voltage balance circuit at various R_f are considered. The simulation results carried out using the MATLAB SIMULINK software showed that the circuit is highly sensitive with ground fault resistances up to R_f = 3 kΩ. It was found that the voltage balance circuit provides protection for 70% of the generator stator winding.

Keywords: synchronous generator, ground fault, third voltage harmonic, relay protection, generator operation regime, voltage balance circuit.

DOI 10.52171/2076-0515_2023_15_02_89_96

Received *30.12.2022*
Revised *19.06.2023*
Accepted *21.06.2023*

For citation:

Abbasov R.M., Manafov E.K., Huseynov F.H.
[Investigation of the voltage balance scheme to protect the generator from ground fault]
Herald of the Azerbaijan Engineering Academy, 2023, vol. 15, no. 2, pp. 89-96 *(in English)*

Generatoru yerlə qapanmalardan mühafizə edən gərginliklər balansı sxeminin tədqiqi

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Xülasə

Məqalədə generatorun stator dolağının gərginliklər balansı sxemi əsasında işləyən mühafizəsinin xüsusiyyətlərinə baxılır. Müəyyən edilmişdir ki, bu sxemin səmərəliliyi generatorun yük rejimindən asılı deyil. Müxtəlif R_f – müqavimətləri üçün generator dolağının yerlə qapanmalar zamanı gərginliklər balansı rejimlərinə baxılmışdır. MATLAB SIMULINK proqram təminatı ilə aparılmış simulyasiya göstərdi ki, R_f = 3 kΩ-a qədər yerlə qapanma müqavimətlər üçün bu sxem yüksək həssaslığa malikdir. Gərginliklər balansı sxemi generatorun stator dolağının 70%-nin mühafizəsini təmin edir.

Açar sözlər: sinxron generator, yerlə qapanma, gərginliyin üçüncü harmonikası, rele mühafizəsi, generatorun iş rejimi, gərginliklər balansı sxemi.

DOI 10.52171/2076-0515_2023_15_02_89_96

УДК 621. 316

Исследование схемы баланса напряжений для защиты генератора от замыканий на землю

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Аннотация

В статье рассматриваются особенности защиты статорной обмотки генератора от замыканий на землю с помощью метода баланса напряжений. Установлено, что эта схема может быть использована вне зависимости от режима нагрузки генератора. Рассмотрены режимы замыкания обмотки генератора на землю для схемы баланса напряжений при различных R_f. Результаты моделирования, проведенного с помощью программного обеспечения MATLAB SIMULINK, показали, что схема обладает высокой чувствительностью при сопротивлениях замыкания на землю вплоть до R_f = 3 kΩ. Выявлено, что схема баланса напряжений обеспечивает защиту 70 % статорной обмотки генератора.

Ключевые слова: синхронный генератор,замыкание на землю, третья гармоника напряжения, релейная защита, режим работы генератора, схема баланса напряжений.

Introduction

As you know, single-phase short circuits of the stator winding to ground are one of the most common types of damage to a synchronous generator. This requires the installation of reliable protections that provide disconnection of the damaged phase of the generator.

The main disadvantage of the circuits used to protect the stator winding of the generator from ground faults is the presence of a "dead" zone. If a fault occurs near the neutral of the generator, the protection trip current may be less than the ground fault current, as a result of which the protection sensitivity will be insufficient to disconnect the damaged phase. Therefore, to ensure the protection of the generator, special circuits are used that respond to changes in the third harmonics of the zero sequence voltage.

According to the above method, the third harmonics of the zero sequence voltage are measured near the neutral and at the terminals of the stator winding of the generator. When a short circuit occurs near the neutral, as it approaches the zero point, the third harmonic decreases to zero, and sharply increases at the terminals. When a short circuit occurs at the winding terminals, the situation is reversed - the third harmonic increases near the neutral and sharply decreases as it approaches the winding terminals. Thus, the ratio of the third voltage harmonics at the terminals and near the neutral $\frac{V_{3t}}{V_{3n}}$ can be used to protect the generator windings from ground faults [1-5, 6-8].

The purpose of the work

The aim of the work is to study the effectiveness of the voltage balance circuit for protecting the stator winding of the generator in case of single-phase ground faults near the neutral. Table 1 shows the nominal parameters of the considered generator.

Table 1 – Generator Ratings

Power (S_n)	850 MVA
Contact resistance (X'_d)	0.43
Supertransient resistance (X''_d)	0.25
Zero sequence inductive reactance (X_0)	0.13
Zero sequence active resistance (R_0)	0.0025
Generator winding capacitance to ground (C_g)	0.128 mkF
Ground resistance (R_n)	1212 Ω
Tire capacity (C_t)	0.1 mkrF
Capacitance between circuit breaker and transformer (C_{cb})	0.25 mkrF
Transformer capacitance (C_{tr})	0.2 mkrF

The voltage balance diagram of the generator-transformer unit is shown in Fig.1.

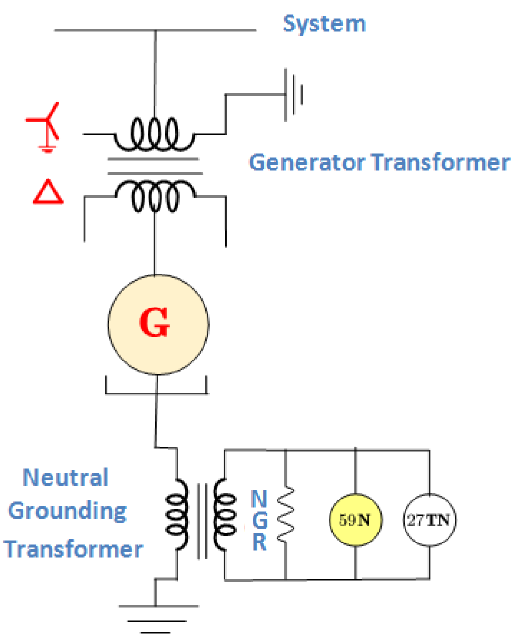

Figure 1 – Scheme of voltage balance

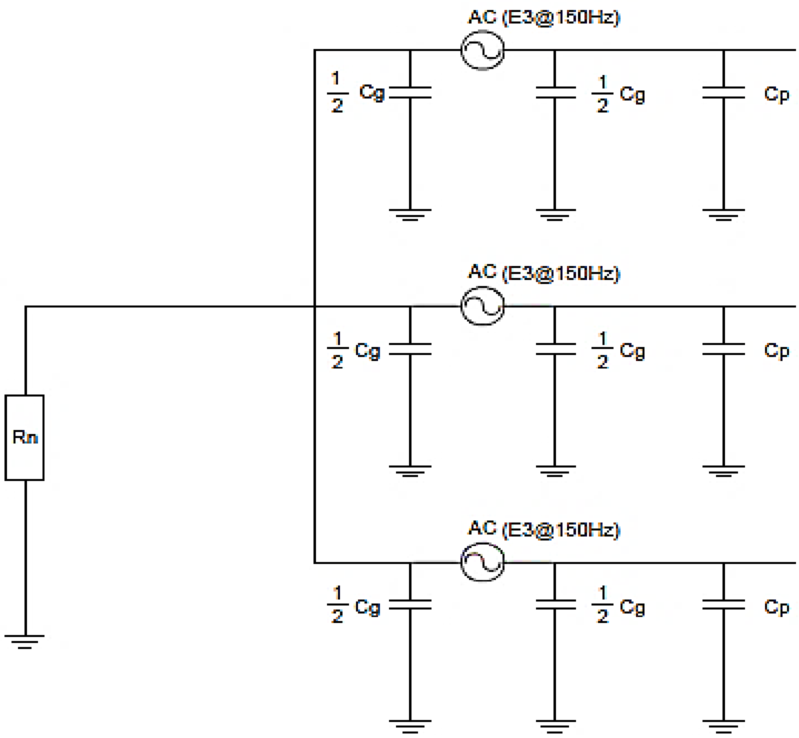

Figure 2 – Generator equivalent circuit in normal regime Consider the circuit for the third harmonics of the zero sequence voltage (Fig. 3).

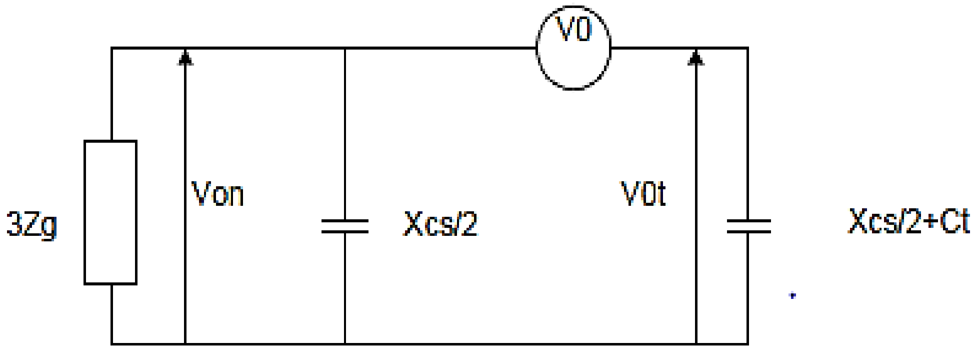

Figure 3 – Zero sequence voltage diagram

A simplified equivalent equivalent circuit of a generator in normal regime is shown in Fig.2. Here C_{ekv} is the equivalent capacitance of the tires, circuit breaker and transformer.

The calculation is made for the values given in Table 1.

$$C_{0n} = \frac{1}{2}C_g = 0.5 \cdot 0.128 \cdot 10^{-6} = 0.642 \cdot 10^{-7}F$$

$$C_{0t} = \frac{1}{2}C_g + C_t + C_{cb} + C_{tr} = \\ = 0.642 \cdot 10^{-7} + 0.55 \cdot 10^{-6} = \\ = 0.614 \cdot 10^{-6}F$$

Capacitances on the neutral and winding terminals.

$$X_{0n} = -j\frac{1}{2 \cdot \pi \cdot f_3 \cdot C_{0n}} = -j16526\Omega$$

$$X_{0t} = -j\frac{1}{2 \cdot \pi \cdot f_3 \cdot C_{0t}} = -j1728\Omega$$

Here f_3 = 150 Hz is the frequency of the third harmonic.

After solving these equations, the impedance near the neutral is calculated.

$$z_{0n} = \frac{-jX_{0n} \cdot 3 \cdot R_n}{3R_n - jX_{0n}} = 3469.18 - j763.48\Omega$$

Typical values of the third voltage harmonics in normal regime at various loads of the generator are given in Table 2 [3-6, 11-13].

Table 2 – Values of the third voltage harmonics in normal regime

Load regime	V_0 (V)
No load	210
Full load	420
Light load	121

Near the neutral, the third harmonic of the voltage:

$$V_{0n} = V_0 \frac{Z_{0n}}{Z_{0n} - jX_{0t}} =$$

$$= 210 \frac{3469.18 - j763.48}{(3469.18 - j763.48) - j1728} = 174.65V$$

At the generator outputs:

$$V_{0t} = V_0 \frac{X_{0t}}{Z_{0n} - jX_{0t}} =$$

$$= 210 \frac{-j1728}{(3469.18 - j763.48) - j1728} = 84.96V$$

The calculation of voltage third harmonics for full load and light load regime is performed in a similar way. The calculation results are shown in Table 3.

Table 3 – Values of the third voltage harmonics in various load regimes

Load regime	V_0 (V)	V_{0n} (V)	V_{0t} (V)
Full load	420	349	169
Light load	121	100	49
No load	210	174	84

The calculation shows that under all load conditions the ratio $\frac{V_{0t}}{V_{0n}} = 0.48$. Therefore, the voltage balance circuit can be applied regardless of the generator operating regime [5-7, 9,10].To analyze the short circuit regime, the third harmonics of the voltage are modeled as 2 sources of alternating voltage (Fig. 4)

Third voltage harmonics near the neutral and at the generator terminals.

$$E_{3n} = kE_3 \qquad (1)$$
$$E_{3t} = (1-k)E_3$$

Here k=0 - 1 is the distance from the neutral to the closing point.

Capacitances C_n and C_t depend on the location of the fault:

$$C_n = k\, C_g \qquad (2)$$

$$C_t = (1-k)\, C_g$$

Consider the short circuit of one phase to ground (Fig. 5).

$$V_n + E_{3n} = (I_1 - I_2)R_f \qquad (3)$$
$$V_t = (I_1 - I_2)R_f + E_{3t}$$

Here R_f - is the ground fault resistance.

$$I_1 = -\frac{V_n}{Z_n} \quad (4)$$

$$Z_n = \frac{-jX_{cn}R_n}{R_n - jX_{cn}}$$

$$V_n = k \cdot E_3 \cdot \left(1 - \frac{R_f}{Z_n}\right) = \quad (5)$$

$$= k \cdot E_3 \cdot \left(1 - \frac{R_f}{R_n - j\frac{1}{2 \cdot \pi \cdot f_3 \cdot k \cdot C_g}}\right)$$

Solving equations (1), (2), (3) and (4) together, we determine the value of the third voltage harmonic near the neutral.

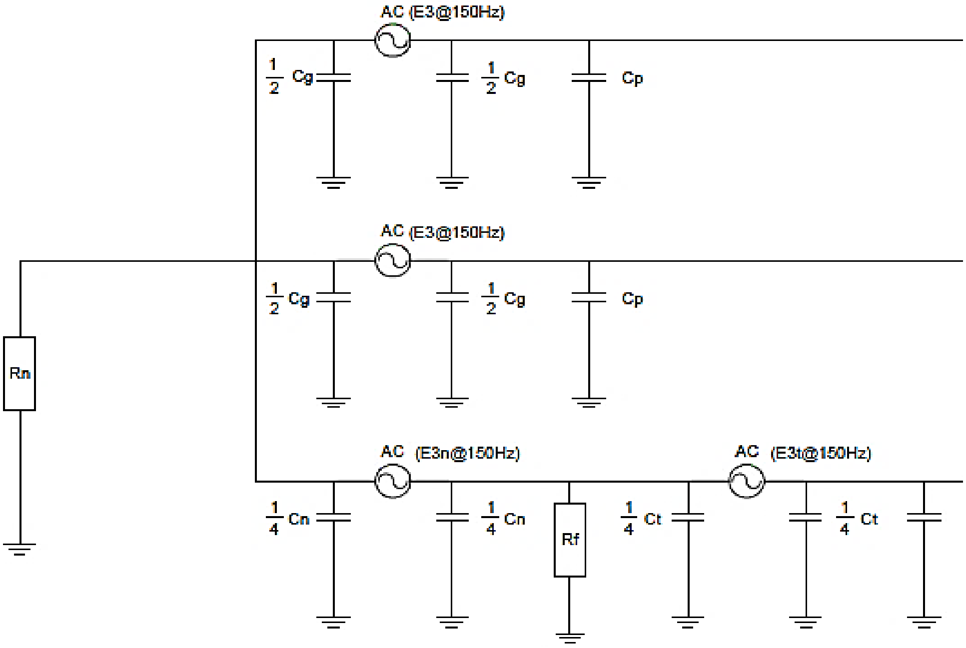

Figure 4 – Ground fault equivalent circuit

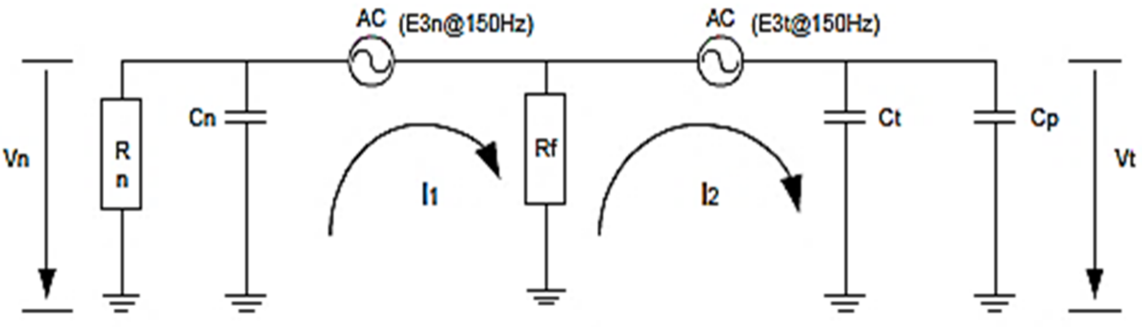

Figure 5 – Equivalent circuit for ground fault regime

Modeling

Let us consider the regime of closing the generator winding to the ground for the voltage balance circuit at various R_f.

The results of the simulation carried out using the MATLAB SIMULINK software are shown in Fig. 6.

The value of the third voltage harmonic at the generator terminals

$$V_t = \left((1-k)\cdot E_3\right) - \left(V_n \cdot \frac{R_f}{Z_n}\right) \quad (6)$$

E_3 is the third harmonic of the generator voltage.

As can be seen, the voltage third harmonics depend on the fault point (k) and the ground fault resistance (R_f).

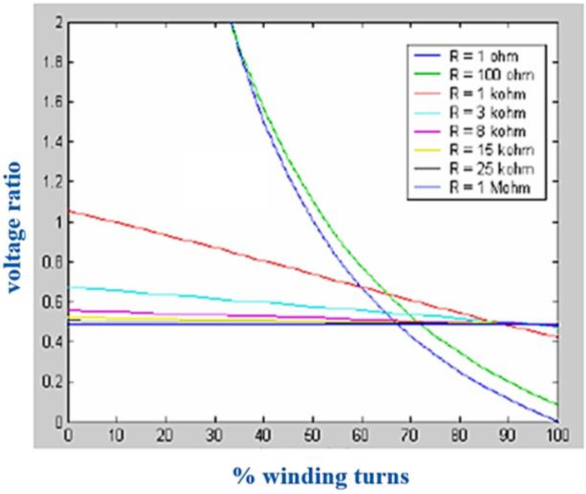

Figure 6 – Dependence of the $\frac{V_{0t}}{V_{0n}}$ ratio on the location of the winding damage

As can be seen, the circuit is highly sensitive for ground fault resistances up to R_f = 3 kΩ. The setting for the voltage relay operation is detuned from the ratio of the third harmonics of the voltage in normal regime.

$$\frac{V_{3t}}{V_{3n}} > k_s V_0 \quad (7)$$

Here k_s=1.2 is the safety factor.

Considering that in normal regime:

$$V_0=0.48,\ \frac{V_{3t}}{V_{3n}} > 0.58.$$

Fig. 7 shows the dependence of the short circuit resistance on the location of the winding damage. As you can see, the voltage balance circuit provides protection for approximately 70% of the stator winding on the neutral side.

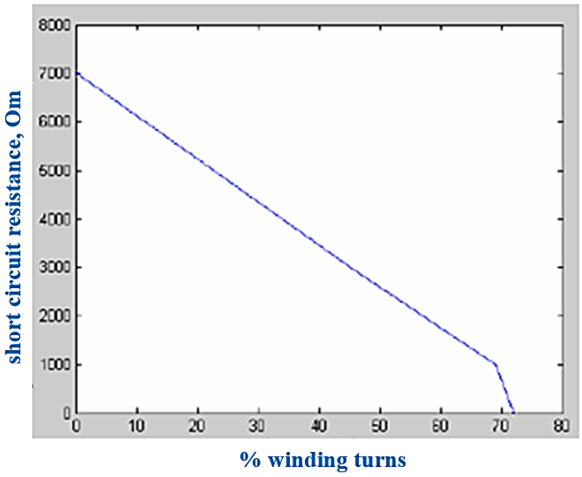

Figure 7 – The dependence of the circuit resistance on the location of the winding damage

Conclusion

The results of the research are shown below. The voltage balance circuit is universal and can be used to protect the stator winding under any generator load conditions. The circuit is highly sensitive with ground fault resistances up to R_f = 3 kΩ. The voltage balance circuit provides ground fault protection for 70% of the stator winding on the neutral side.

Conflict of Interests

The authors declare there is no conflict of interests related to the publication of this article.

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