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SELF-EXCITING CAPACITOR CIRCUIT FOR A LOW-POWER, LOW-SPEED SINGLE-PHASE INDUCTION GENERATOR

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ABSTRACT

It is not easy to generate voltage in a low-power, low-speed induction generator without initial voltage on its excitation capacitor. A special circuit needs to be designed to create an initial charging of capacitor if it is to be used for pico/microhydro power generation in remote area. During start-up process, the resulted waveform of capacitor current is almost always of damped sinusoid because the energy transferred between capacitor and inductor is continuously decreasing and becoming heat losses in the resistor. Highly damped of current is not desired as there will be no enough charges remaining to initiate the voltage and power generation. Experiment results indicate that it needs at least the amplitude reduction up to about 20% after five cycles - being equivalent to 0.1 second for a 50-Hz system frequency - to obtain a successful starting-up of the low-power, low-speed single-phase induction generator considered in this paper.

Keywords: induction generator, battery, capacitor, thyristor, triggering circuit.

INTRODUCTION

Induction generator will only generate active power (in watts) if its need of reactive power is fulfilled from any additional source. Capacitors can be used in this matter to enable the self-excitation and generation of voltage (in volts) and active power (in watts) of the generator [1-4].

A low-power low-speed single-phase induction generator (SEIG) being obtained from a winding-modified capacitor motor could not self-excite to generate voltage, although its voltage remnant reached 2% of its nominal value. Some initial voltage as much as its nominal value should be applied to its exciting capacitors [5-6].

When the generator is to be used in micro/pico-hydro power plants in remote areas, supplying an initial voltage of the nominal value during starting-up could pose a problem. Consequently, recourse to a specific excitation system being equipped with a capacitor charging circuit using an easily available voltage supply should be taken [7].

Voltage generation

In general, the voltage induction on the windings of generators or transformers can be understood based on the Faraday induction principle [8-9].

$$e = -N\frac{d\Phi}{dt} \tag{1}$$

$$\Phi = BxA \tag{2}$$

where e instantaneous induced voltage [volt]
N winding turns-number
Φ magnetic flux [weber]
B magnetic flux density [weber/m^2]
A cross-section area [m^2]

The induced voltage on a conductor bar of generator which cuts across the magnetic field direction perpendicularly can be found as,

$$E = Blv \tag{3}$$

The induced voltage on a phase winding of a generator can be calculated using [9]:

$$E = 4.44\, f\Phi NK \tag{4}$$

where f frequency [hertz]
l conductor active length [m]
v linear velocity [m/s]
K coefficient depending on the winding form

Voltage drop and winding power losses

Physically, low-power induction generator will have larger diameter and less core length than high power generator with the same rotation speed. Consequently, there will be less magnetic cross-section area. For the same magnetic flux density, it requires more winding turns to generate higher voltage.

Under the same operating voltage, generator with lower capacity will have lower current, so that it requires smaller conductor cross-section area. As a result of higher winding-turns number and smaller conductor cross-section area, there will be higher winding impedance, especially its resistance. The high value of stator winding impedance (R_1+jX_1) will bring about high voltage drop and power losses on the windings. Figure-1 shows an equivalent circuit of induction generator under loading condition.

It can be known that the induced voltage can be approximated with the winding voltage, $E \approx V_m$. The voltage across the generator terminals,

$$V_1 = V_m - (R_1 - jX_1)I_1 \quad \text{volt} \tag{5}$$

The power losses on the stator winding,

$$P_{Cu} = I_1^2 R_1 \text{ watt} \tag{6}$$

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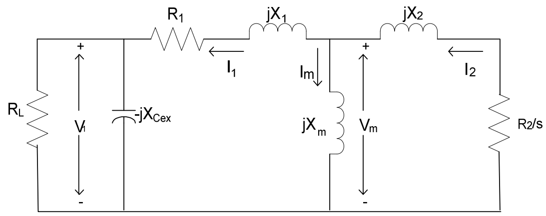

Figure-1. An equivalent circuit of induction generator under loading condition [8].

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Starting-Up of SEIG

In the early moments of the starting-up process of SEIG, the relationship between the exciting capacitor and the phase-winding of the generatpr can be approximated using a closed series circuit between a resistor (*R*), an inductor (*L*) and a pre-charged capacitor (*C*). In this condition, there would be capacitor discharge current being commonly called as natural current. It is not resulted from an external voltage supply, but because of the stored energy due to the electric field in the capacitor. Depending on the value of the related component (*R*, *L* and *C*), the natural current could be overdamped, critically damped, or underdamped (as shown in Figure-2).

The natural current can be expressed using Eqn.(7).

$$i_n = I_1 e^{s_1 t} + I_2 e^{s_2 t} \quad \text{ampere} \qquad (7)$$

where s_1 and s_2 can be found by equaling the voltage equation to zero, $v = Z\, i = 0$, which can be met only if the impedance Z is of zero value, as the current *i* cannot be zero.

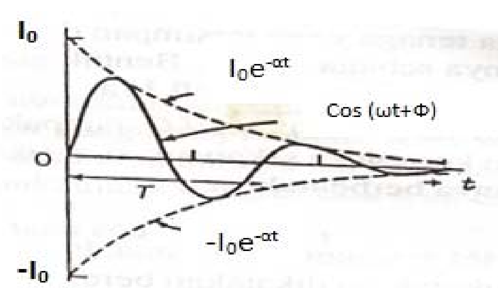

Figure-2. An underdamped sinusoidal waveform [10].

For a series circuit of RLC,

$$Z(s) = R + sL + \frac{1}{sC} \qquad (8)$$

so that in order to get Z(s)=0, then $s^2LC+sCR+1=0$.

By solving the quadratical equation, the roots can be found,

$$s_{1,2} = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} \qquad (9)$$

If $\frac{1}{LC} > \left(\frac{R}{2L}\right)^2$ then complex roots will be obtained,

$s_1 = -\alpha + j\omega$ and $s_2 = -\alpha - j\omega$, where $\alpha = \frac{R}{2L}$ is the damping factor of the wave amplitude, and

$\omega = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$ is the natural angular frequency.

For an underdamped condition, the natural current can be expressed using Equation [10].

$$i_n = I_0 e^{-\alpha t} \cos(\omega t + \varphi) \quad \text{ampere} \qquad (10)$$

where I_0 and φ can be found from the initial conditions.

Certain natural current with small amplitude damping is required during the initial moments of starting-up generator, in order to trigger and to enable the self-excitation phenomenon result in voltage generation in a low-power low-speed single-phase induction generator. As a consequence, sufficient capacitor voltage (as much as its nominal value) and as low as possible of winding resistance are needed [5-6].

Capacitor charging circuit

For the operation of power plants in remote areas, the requirement of large direct-current voltage source is not easy to fulfill. A special charging system for the excitation capacitors should be provided. This paper presents an idea to use some capacitors, which could be assembled as shown in Figure-3, and some battery type which is readily available around the area.

If direct-current voltage supply of the nominal value (220 volts) is not available or difficult to procure, a specific circuit must be provided for the purpose of initial charging of potential capacitors C_p. This circuit should be equipped with electronic switches (thyristor) to facilitate the connections between capacitors in parallel, and then being converted into series connection.

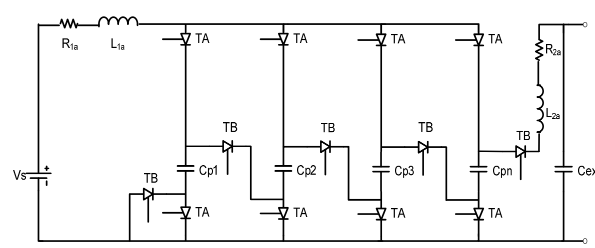

Figure-3. Circuit of the triggering capacitor C_p to charge the excitation capacitor C_{ex}.

In Figure-3, R_{1a} and R_{2a} represent the windings resistance to protect thyristor from the high value of

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maximum flowing current, while L_{1a} and L_{2a} represent the windings inductance to protect from any instantaneous change of current. Their values are chosen based on the capacity of the available battery.

Simultaneous triggering of all thyristors TAs will connect all capacitors C_{p1}, C_{p2}, C_{p3}, up to C_{pn} in parallel, as shown in Figure-4, and also simultaneously connect them to the battery.

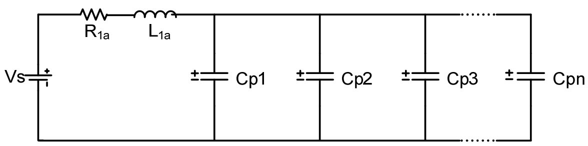

Figure-4. The charging process of the triggering capacitors being connected in parallel to battery V_S.

The resistors R_{a1} is required as a current limiter to avoid short-circuit to happen. Current will flow from the battery to all the triggering capacitors in a very short time and the thyristor turns off automatically. This happens because of the load commutation being caused by the cessation of the flowing current at the time the triggering-capacitor voltage equals the battery voltage, $V_{Cp} = V_S$.

With the extinction of all thyristors TAs, all the triggering capacitors will be disconnected from each other including from the battery, but there will still be voltage equal to the battery voltage on each capacitor.

The charging process of excitation capacitor C_{ex} is performed by triggering all thyristors TBs simultaneously so that all triggering capacitors C_{p1}, C_{p2}, C_{p3}, up to C_{pn} will be connected in series including with the excitation capacitor C_{ex} through resistor R_{a2} and inductor L_{a2}, as shown in Figure-5.

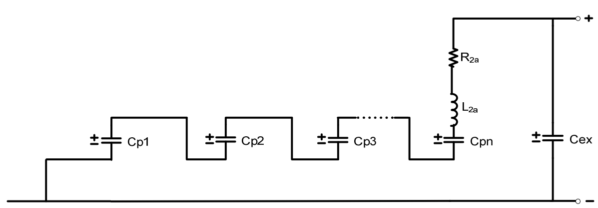

Figure-5. The charging process of the triggering capacitors C_{ex} using the series connected capacitors C_p.

Under the condition shown in Figure-5, the current flows from a number of triggering capacitors connected in series to the excitation capacitor through a current-limiting resistor R_{a2}. The thyristor TB will be turned-off instantaneously because of load commutation due to the current extinction at the time the excitation capacitor voltage equals the voltage of the triggering capacitors in series connection.

$$V_{Cex} = V_{Cp1} + V_{Cp2} + V_{Cp3} + ... + V_{Cpn} \quad (11)$$

The values of C_{p1}, C_{p2}, C_{p3}, up to C_{pn} depend on the required voltage value and the available battery capacity. The value of C_{ex} depends on the generator equivalent parameters values.

Turning-off all thyristors TBs enables the excitation capacitor C_{ex} to be released from the triggering capacitors and to be ready for starting up the self-excited low-power low-speed single-phase induction generator.

METHODS AND EXPERIMENTS SET-UP

The conducted research involved an experimental study, which required to design and to construct a triggering capacitor circuit for excitation capacitor of a low-power low-speed single-phase induction generator.

Table-1 shows the nameplate data and machine parameters obtained through some standard measurements and testings, including block rotor test and no-load test.

The circuit arrangement during experiments is shown in Figure-6, whereas the set-up during the variables measurements is shown in Figure-7.

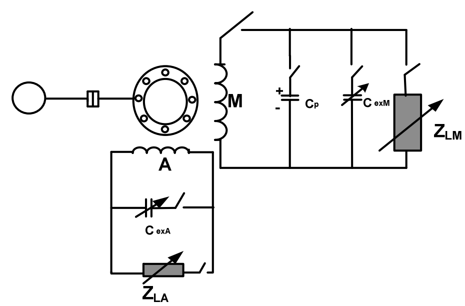

Figure-6. The experiments set-up using the triggering capacitor C_p and the excitation capacitor C_{ex}.

Figure-7. The measurement of variables in laboratory.

Before starting-up, all switches must be opened and the excitation capacitor C_{ex} must be pre-charged separately. Initial triggering is only done on the excitation capacitor of the main-winding, while no initial voltage is required on the excitation capacitor of the auxiliary-winding. However, it should have been connected to the generator winding before the starting-up and the load should have been disconnected. Once the generator

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voltage reaches its steady-state condition, load can be added gradually.

Table-1. Data of machine used in the experiments.

Symbol	Quantity	Value	Unit
P	generator output power	500	[watt]
D_s	stator inner diameter	105	[mm]
D_r	rotor outer diameter	104	[mm]
L	stator core length	85.5	[mm]
S	Stator slots number	36	[-]
p	Pole-number	12	[-]
V_{nom}	Nominal voltage	220	[volt]
$Z_{ek.m}$	Equivalent impedance of the main-winding	54.50	[Ω]
$R_{ek.m}$	Equivalent resistance of the main-winding	15.00	[Ω]
$X_{ek.m}$	Equivalent reactance of the main-winding	52.39	[Ω]
C_M	Capacitor of the main-winding	48	[μF]
$Z_{ek.A}$	Equivalent impedance of the auxiliary-winding magnetization	63.00	[Ω]
$R_{ek.A}$	Equivalent resistance of the auxiliary-winding	32.00	[Ω]
$X_{ek.A}$	Equivalent reactance of the auxiliary-winding	54.27	[Ω]
C_A	Capacitor of the auxiliary-winding	24	[μF]

RESULTS AN ANALYSIS

The circuit arrangement of the triggering potential capacitor C_p depends on the available battery voltage, the number of series-connected capacitors and the excitation capacitance C_{ex}. If there are n triggering capacitors C_p connected in series, then the capacitance of each C_p is equal to n times the excitation capacitance C_{ex} ($C_p = n.C_{ex}$). The waveform and amplitude of the initial excitation current during the starting-up process are determined by the initial voltage, the excitation capacitance, and the equivalent resistance and inductance of the induction generator.

Using the data in Table-1 (X=52.39 Ω) and by calculating based on frequency 50 Hz of the testing voltage ($X=2\pi fL$), the the main-winding equivalent inductance is obtained to be L=166.86 mH. By using Equation (9) and Equation (10), the natural response equation of the current is obtained as:

$$i_n = I_0 e^{-44.95t}\cos(350.55t + \varphi) \text{ ampere}$$

where using the initial condition of the circuit will result in $I_0 = -3.761$ and $\varphi = 90^o$, so that the natural response of initial exciting current becomes Equation (10):

$$i_n = -3.761 e^{-44.95t}\cos\left(350.55t + 90^o\right) \text{ ampere}$$

Figure-8 indicates the exciting capacitors current waveform during the discharging process to the generator. It shows a natural response of current which is damped with fundamental frequency of 51-Hz.

During the first five cycles or about 104ms there are still apparent oscillation amplitudes, indicating the remaining available potential to generate voltage.

During the starting-up, the transition between the charges in the capacitors being indicated with the capacitor voltage value to those in the form of induction generator voltage under steady-state condition is shown in Figure-9.

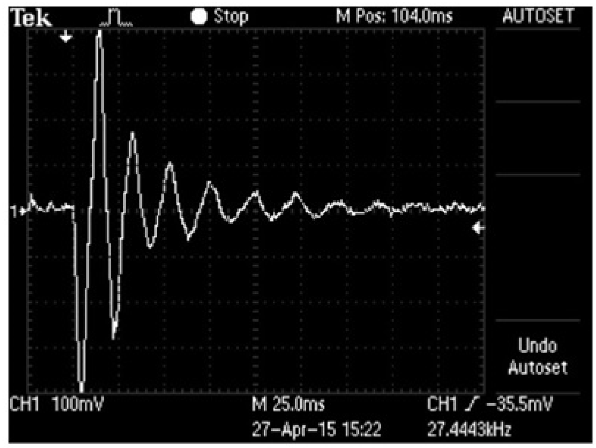

Figure-8. Experiment result of the natural response of excitation capacitor current of machine under consideration.

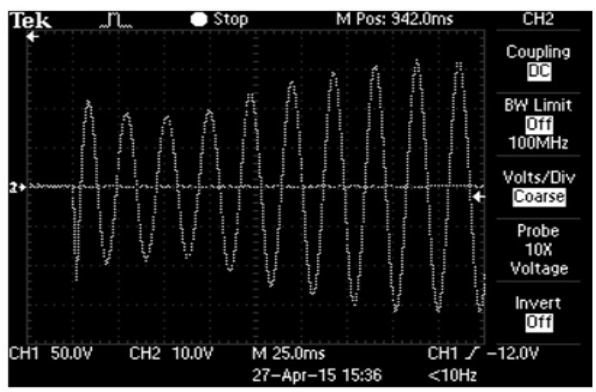

Figure-9. Experiment result of the building-up of generator voltage under consideration.

It indicates that during the first four cycles there has been certain reduction of voltage amplitude brought about by the reduction in amplitude of excitation current oscillation which was still available and not collapsing. Consequently, the prevailing excitation current is supporting the building-up of generator voltage until reaching its final steady-state value.

CONCLUSIONS AND PERSPECTIVES

Based on the analysis of experiment data and calculation results, some conclusions can be drawn as follow.

- The transient oscillation of the excitation current depends on the initial voltage and capacitance of the exciting capacitors as well as the equivalent resistance and inductance of the induction generator.
- Starting-up of induction generator could be achieved whenever the natural response of exciting-capacitor discharging current is not overly damped, giving enough time to build-up voltage – at least five cycles after the first maximum current value giving the remaining amplitude of about 20%.
- The configuration of excitation capacitors is determined by the available battery voltage as well as the capacitance and the number of capacitors to be connected in series.
- During the starting-up process, all connected loads and measuring equipments are prone to discharge the exciting capacitors bringing about the failure in generating voltage.

In order to reduce the steepness of initial exciting-capacitor transient-current oscillation-envelope, generator with as low resistance as possible should be considered. In addition, loads with capacitive characteristics should be chosen in order that each automatic load increase could be counterbalanced using reactive power supply from loads, so that any voltage collapse could be avoided.

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