VOLTAGE CONTROL OF SELF-EXCITED INDUCTION GENERATOR DRIVEN BY WIND SPEED

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Abstract

This paper presents a theoretical and experimental analysis of a stand alone wind energy system using three phase squirrel cage self excited induction machine. The condition of self-excitation process of the three-phase induction generator is reviewed. The voltage of the induction generator is regulated according to operating speed range through capacitor banks. The generator regulated voltage is then rectified, regulated using a single phase push pull step down dc chopper, inverted using a single phase push pull inverter and then transformed up so as to feed an isolated single phase ac load with stabilized voltage whose magnitude and frequency are constant. Avoiding bad weather conditions is considered by using back up battery, which is charged from the wind at normal weather conditions. The system is practically implemented and experimental results are obtained. MATLAB-SIMULINK software is used to simulate the system and the transient response of the output voltage due to step change of generator voltage is presented.

مقدمة

هذا البحث يقدم دراسة نظرية مع التطبيق العملي لنظام التحكم في جهد و تردد مولد الحث الذاتي الإثارة. تم مراجعة الشرط اللازم لتحقق الإثارة الذاتية لمولد الحث من اجل حساب قيم المكثف اللازمة للتحكم في القيمة العظمى و الصغرى لجهد المولد للمحافظة على تنظيم جهدي مناسب و لحماية المولد من ارتفاع شديد للجهد نتيجة زيادة سرعة الدوران. تعتمد فكرة البحث على توحيد جهد المولد المتغير ثلاثي الوجه إلى جهد مباشر ثم تنظيمه على جهد منخفض ثم تحويله إلى جهد متغير بقيمة جهد و تردد ثابتين. لضمان المحافظة على تغذية الحمل أثناء انخفاض سرعة الريح تم استخدام بطارية يتم شحنها أثناء ظروف التشغيل العادية. يتم رفع الجهد للحمل إلى الجهد المطلوب عن طريق محول رافع. تم تمثيل النظام المقترح بأنموذج تحليلي باستخدام الحاسب الآلي وتم استنتاج الاستجابة اللحظية لجهد الحمل عند تغير المفاجئ في جهد المولد. تم تطبيق المنظومة المقترحة عمليا و استنتاج النتائج.

KEYWORDS: Induction generator – Wind energy – Voltage control – Frequency control.

LIST OF SYMBOLS

R_s, X_{ls} : stator resistance and leakage reactance per phase

R_r, X_{lr} : rotor resistance and leakage per phase referred to stator

X_m, X_c : magnetizing reactance referred to stator and capacitive reactance per phase

R_L, X_L : load resistance and reactance

F, υ : per unit frequency and speed

j, p : complex and differential operators

V_g : air gap no load voltage

I- INTRODUCTION

Increasing rate of depletion of conventional energy resources has increased the concentration on renewable energy resources such as wind, solar and hydro. Researches have been carried out on different electrical machines that could be used as energy converter in such systems [1]. The notable advantages of induction generator over other machines are robustness, absence of moving contacts, and no need for DC excitation [2]. When an induction machine is driven at a speed greater than its synchronous speed, negative slip, the direction of the induced torque is reversed and theoretically it start working as induction generator. In this negative slip region, the machine draws a current, which lag the voltage by more than 90^o. This mean that real power flow out of the machines but the machine needs reactive power [3]. To build up voltage across the generator terminals, excitation must be provided by either reactive power drawn from the grid in case of grid connected induction generator or from suitable capacitor bank connected across the generator terminals in case of stand alone (isolated) induction generator [4]. The later phenomenon is known as capacitor self-excitation. Many researches have been done on the capacitance requirements of self-excited induction generators [5-6]. In [5] a trial and error method based on the steady state equivalent circuit model was used to determine the required capacitance. Calculation of the minimum capacitance required for self-excitation using flux model has also been reported [6]. The main problem in using a Self Excited Induction Generator (SEIG) is the control of the generated voltage because the voltage magnitude and frequency drop with increasing load as well as with a decrease in the wind speed driving the generator. This problem could be solved in wound rotor induction generator using controlled rotor excitation [7] or by varying the rotor resistance [8]. However a self-excited wound rotor induction generator will require more maintenance than a squirrel cage rotor due to the slip rings and brushes. In squirrel cage SEIG, the magnitude of the generated voltage could be controlled using variable capacitor values [9], irrespective of its frequency, or a fixed capacitor with thyristor controlled reactor static VAR compensator [10], or continuously controlled shunt capacitors using anti-parallel IGBT switches across the fixed excitation capacitor [11]. The main objective of this study is to regulate the output of squirrel cage SEIG to supply an AC load with 220V and 50 Hz with acceptable voltage regulation. The proposed system has no mechanical speed control or blade pitch control, and hence the generated voltage from induction generator will be characterized by variable magnitude and frequency and therefore self-excitation may cause severe voltage fluctuations thereby stressing the insulation of the machine. Also, it can cause torque and speed fluctuations, which affect the performance of the machine and might cause significant over heating. The condition of self-excitation is reviewed and the relationship between no load voltage and speed is analyzed to predict a suitable value for excitation capacitor to regulate the generator voltage for each speed range. The schematic diagram of the proposed system is shown in fig. (1) where the system has no speed control. Capacitor banks are connected to the machine to regulate the generator voltage using relays whose control signals are produced by a multi stage comparator circuit, which compares actual speed signal with preset values. Three phase uncontrolled bridge rectifier is used to convert AC regulated generator voltage to DC. Then a push pull DC-to-DC single quadrant chopper is used to step down and regulate the dc voltage which is then stored in a back up battery at low voltage to allow power conversion from the generator even at low wind speed. The base signals of the two power transistors of the dc chopper are controlled through a feed back signal from a battery using pulse width modulation controller [12]. The regulated dc power is converted to an ac power using a single-phase inverter, which uses a pulse-width modulation controller with a feed back signal from output load voltage. A step up transformer is then used to raise the voltage and a low-pass filter eliminates the harmonics from the load voltage. The system is experimentally implemented and theoretically simulated using MATLAB software and the transient response due to step change of generator voltage is presented.

II- VOLTAGE CONTROL OF INDUCTION GENERATOR

In the self-excitation mode, the generator output frequency and voltage are affected by the speed, load and capacitance value [16]. Wind energy systems are classified into constant speed constant frequency system (CSCF) and variable speed variable frequency systems (VSVF). Mechanical control or blade pitch control is used in CSCF systems to provide constant speed. Thus, this system is used to supply load with constant voltage and constant frequency. The main characteristic of VSVF system is the use of VAR controller used for excitation and voltage control [21]. Stand-alone wind energy system may use a controlled inductor in parallel with a capacitor to provide self-excitation, and to control the terminal voltage [10].

A. CONSTANT VOLTAGE OPERATION

The generator voltage can be regulated according to operating speed range through capacitor banks. The equivalent circuit per phase at steady state, shown in fig. (2) [14], is used to predict the excitation capacitor required to regulate no load voltage for each speed range. Noting that the equivalent impedance of the equivalent circuit must equal to zero and substituting for 'F' by '–jω' into fig. (2), the following expression can be concluded:

$$Z_{eq}=\frac{X_m p\left(X_{lr}p+\dfrac{R_r}{1-{}^{j\nu}\!/_{p}}\right)}{\dfrac{R_r}{1-{}^{j\nu}\!/_{p}}+X_{lr}p+X_m p}+R_s+X_{ls}p+\frac{(R_l+X_{;}p)\,{}^{X_C}\!/_{P}}{R_l+X_l p+{}^{X_c}\!/_{p}}=0 \qquad (1)$$

The corresponding characteristic polynomial is:

$$K_4 p^4 + K_3 p^3 + K_2 p^2 + K_1 p + K_0 = 0 \qquad (2)$$

Where coefficients $K_4 \ldots K_0$ are constants and defined in Appendix (A). For a given wind speed and load impedance, the critical value or minimum capacitance required for self excitation can be evaluated by calculating the roots of polynomial of (2) [14]. For the induction generator whose details are given in Appendix (B), the variation of the magnetization reactance versus the air gap voltage at synchronous speed is best fitted and given by.

$$V_g / F = 300 - X_m \qquad \text{For} \quad X_m < 100 \qquad (3)$$

Knowing magnetizing reactance X_m, the corresponding gap voltage is obtained from (3). The terminal voltage, stator current, load current and output power can be concluded using equivalent circuit of fig. (2). Fig. (3) shows the relationship between no load line voltage and speed for different values of excitation capacitor. It can be noticed that the generated voltage increases with the increase of the amount of capacitance connected across machine terminals. Therefore the generated voltage may be controlled by the controlling of the amount of capacitor connected across the machine terminals when the wind speed changes. The no load voltage can be kept between upper and lower limits for each speed range by controlling the amount of excitation capacitor. The software program, whose flow chart is shown in fig. (4) predicts the relationship between no load voltage and speed as shown in fig. (5). The results showed that for a speed range from 500 rpm to 1200 rpm, the no load line voltage is regulated between 198V to 242V (i.e: 220±10%) with in five speed ranges each of which has corresponding excitation capacitor necessary to keep no load voltage between upper and lower limit to protect machine from over voltage and improve voltage regulation. The regulated machine voltage is rectified and then dc chopped down to control voltage level constant.

B. CONSTANT FREQUENCY OPERATION

The frequency of the induction generator depends on capacitor, speed and load. To eliminate the effect of changing the frequency, the three–phase voltage from the induction generator is converted to dc using an uncontrolled three-phase rectifier. The DC rectified voltage is DC chopped down then converted to ac voltage through a single-phase inverter whose frequency is controlled.

III- EXPERIMENTAL IMPLEMENTATION

The schematic diagram of the circuit shown in fig. (1) is experimentally implemented. The three-phase induction generator is connected to permanently a 3-phase capacitor bank of 40 μF, which enables self-excitation for speed range higher than 500 rpm. Five 3-phase capacitor banks whose values are shown in fig. (5) are connected in parallel to the generator through relays to regulate the generator line voltage with in ±10% rated voltage for speed range from 500 rpm to 120 rpm. The control signals of the relays are produced automatically by a multistage comparator circuit, which compares actual shaft speed signal with a preset value. The output-regulated voltage of the induction generator is rectified using 3-phase uncontrolled bridge rectifier. Since the ratio between average dc voltage output from bridge and RMS value of the input line voltage is given by $3/(\sqrt{2}.\pi)$ [7], the dc rectified voltage changes between 133.7V and 163.4V with in the operating speed range. The rectified voltage is filtered using low pass second order L-C filter. The filter capacitor is selected 5100 μF/380VDC. The filter inductance is selected 5mH/15A to maintain filter ripple factor of 10% [17]. A push pull dc-dc converter, shown in fig. (6), is used to step down the voltage to a smooth constant value of 27.6V equal to the floating value of the lead acid back up battery where in wind energy system, it is convenient to use a back up battery to supply load in case of wind stall such that the battery is charged from the generator during normal operation. The step down transformer of the dc chopper has turns ratio of 4:1 which is the nearest ratio of the minimum DC rectified voltage to floating value of the battery voltage. A push pull single-phase inverter shown in fig. (7) is used to convert DC voltage to AC voltage to supply the single-phase load with 220V, 50Hz AC voltage. The control signals to the base of the BJT switches of both the DC chopper and the inverter are produced by comparing a feed back signal from the voltage of the battery and the AC load respectively with reference values. The output error signals from the two comparators are then applied to PI controllers whose outputs are compared with saw tooth waves to pulse width modulate the signals and generate square pulses whose chopping frequency 5 kHz and the operating frequencies are 250 Hz and 50 Hz respectively. A soft starting technique is used to reduce inrush current of the transformer in the DC chopper and to protect the power transistor by generating the comparator output signal initially narrow pulses then increasing width gradually. A step up transformer whose ratio is 1:12, which is the nearest value of the floating value of the battery and the maximum value of the output voltage, raises the ac voltage to 220V. The inverter output voltage is a rectangular waveform. A series parallel resonant L-C filter is used to eliminate harmonics. The corner frequency of the filter is $2\pi.100$ rad/sec, which is double the output frequency, and filter ripple factor is 10% [17]. Therefore, the capacitance and the inductance of the series branch are 60 μF and 168 mH and those of the parallel circuit are 20 μF and 506 mH. The parts of figure (8) show experimental results from the system.

IV- SIMULATION and TRANSIENT RESPONSE

The system shown in fig. (1) is simulated using SIMULINK software. When the wind speed is decreased, the generator voltage and frequency are consequently decreased up to certain value at which extra amount of excitation capacitor is implemented which will result in increasing voltage and frequency. This condition can be simulated to study the transient performance of the circuit due to step change of the generator voltage in both frequency and magnitude. The parts of fig. (9) show the voltage waveform in different places of the circuit due to step change in input voltage magnitude from 200 V to 220 V and in the input voltage frequency from 50 Hz to 60 Hz. It is seen that the system output voltage is not affected by input voltage variation meaning that the load is fed by a stabilized voltage irrespective of the variation of wind speed.

V - CONCLUSIONS

The use of induction machine as a self excited induction generator requires a prime mover, sufficient amount of excitation capacitor and amount of residual magnetism stored on the machine core. The system input is a wind speed and system output is 220V and 50Hz single-phase voltage. The operational equivalent circuit of the machine has been used in the analysis to identify the steady state analysis. The output voltage from the induction generator can be regulated within certain limits by controlling the excitation capacitance according to speed range to protect machine from over voltage. A speed range between 500 rpm to 1200 rpm requires excitation capacitance of 40μF to 380 μF. Excitation control has been employed five step capacitor banks connected to induction machine using relays not to exceed the voltage 10% above rated machine voltage within speed range. The control signal of the relays are produced by a multi stage comparator circuit, which compares actual speed signal with preset values. The regulated voltage from the generator is rectified using a 3-phase uncontrolled bridge rectifier. A single-phase push pull step down chopper is used to control dc voltage at a constant level to allow power conversion even at low wind speed. A battery is used as a back up source to wind energy, which improves voltage regulation due to its controlled constant voltage such that at normal operation conditions, battery is charged from the generator. A push pull inverter and step up transformer are used to convert dc voltage into 220v, 50Hz stabilized voltage to feed a single-phase load. The control pulses the chopper and the inverter are produced a PWM feed back control technique to generate square pulses whose chopping frequency is 5kHz while the fundamental frequencies are 250 Hz and 50 Hz respectively. A fourth order series-parallel filter is used to eliminate harmonics from load voltage. A computer simulation using MATLAB-SIMULINK software package has been developed to analyze the steady state performance of a capacitor self excited induction generator. The transient response of the output voltage due to step change of generator voltage and output load are presented.

VI -REFERENCES

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VII - APPENDIX (A)

Induction machine ratings and parameters are:

3-phase, Y-connected, 380V, 2.2 kW, 0.85 PF, 4 Poles, 50 Hz

R_s, X_{ls} : 1.9, 2.45 Ω/phase R_r, X_{lr} : 2 , 2.45 Ω/phase

Xm : 100 Ω/phase (unsaturated)

VIII - APPENDIX (B)

$$K_1 = -jX_L X_l X_s$$

$$K_2 = -\nu\, X_L X_l (2 * X_m - X_l) - j[X_L (R_s + R_r) X_s + X_l R_L (2X_m + X_l)]$$

$$K_3 = -\nu\, X_l R_L (2X_m + X_l) - \nu\, R_s X_L X_S - j[X_l X_c (2X_m + X_l) + R_L X_s (R_S + R_r)]$$

$$K_4 = -\nu[X_c X_L X_S + R_S R_L X_S + X_l X_C (2X_m + X_l)] - j[X_C X_S (R_L + R_S + R_r) + R_S R_r R_L + X_C X_L R_r]$$

$$K_5 = -\nu X_c X_S (R_S + R_L) - jX_C R_r (R_S + R_r)$$

Where $X_S = X_m + X_r$

And $X_{lr} = X_{ls} = X_l$