Conference Paper

November 2004 • NREL/CP-500-33138

Self Excitation and Harmonics in Wind Power Generation

Preprint

E. Muljadi and C.P. Butterfield
National Renewable Energy Laboratory

H. Romanowitz
Oak Creek Energy Systems, Inc.

R. Yinger
Southern California Edison

To be presented at the 43rd AIAA Aerospace Sciences Meeting and Exhibit
Reno, Nevada
January 10–13, 2005

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Self Excitation and Harmonics in Wind Power Generation

E. Muljadi and C.P. Butterfield[*]
National Renewable Energy Laboratory, Golden,, Colorado, U.S.A.

H. Romanowitz
Oak Creek Energy Systems Inc., Mojave, California, 93501, U.S.A.

and

R. Yinger
Southern California Edison, Rosemead, California, 91770 U.S.A.

***Abstract*—Traditional wind turbines are equipped with induction generators. Induction generators are preferred because they are inexpensive, rugged, and require very little maintenance. Unfortunately, induction generators require reactive power from the grid to operate and some capacitor compensations are often used. Because reactive power varies with the output power, the capacitor compensation is adjusted as the output power varies. The interactions among the wind turbine, the power network, and the capacitor compensation, are important aspects of wind generation. In this paper, we will show the interactions among the induction generator, capacitor compensation, power system network, and magnetic saturations and examine the cause of harmonic currents and self-excitation.**

I. Introduction

MANY of today's operating wind turbines have fixed speed induction generators that are very reliable, rugged, and low cost. During normal operation, an induction machine requires reactive power from the grid at all times. Thus, the general practice is to compensate reactive power locally at the wind turbine and at the point of common coupling where the wind farm interfaces with the outside world. The most commonly used reactive power compensation is capacitor compensation. It is static, low cost, and readily available in different sizes. Different sizes of capacitors are generally needed for different levels of generation. A bank of parallel capacitors is switched in and out to adjust the level of compensation. With proper compensation, the power factor of the wind turbine can be improved significantly, thus improving overall efficiency and voltage regulation. On the other hand, insufficient reactive power compensation can lead to voltage collapse and instability of the power system, especially in a weak grid environment.

Although reactive power compensation can be beneficial to the overall operation of wind turbines, we should be sure the compensation is the proper size and provides proper control. Two important aspects of capacitor compensation, self-excitation[1, 2] and harmonics[3, 5], are the subjects of this paper.

In section II, we describe the power system network, in section III, we discuss the self-excitation in a fixed-speed wind turbine, and in section IV, we discuss harmonics. Finally, our conclusions are presented in section V.

II. Power System Network Description

We investigated a very simple power system network consisting of one 1.5 MW, fixed-speed wind turbine with an induction generator connected to a line feeder via a transformer (2 MVA, 3 phase, 60Hz, 690V/12kV). The low-speed shaft operates at 22.5 rpm and the generator rotor speed is 1200 rpm at its synchronous speed.

A diagram representing the system we investigated is shown in Figure 1. The power system components analyzed include the following:

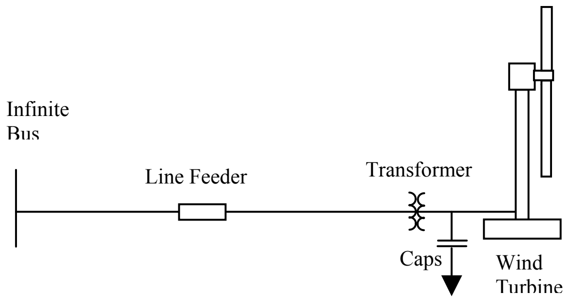


Fig. 1. The physical diagram of the system under investigation.

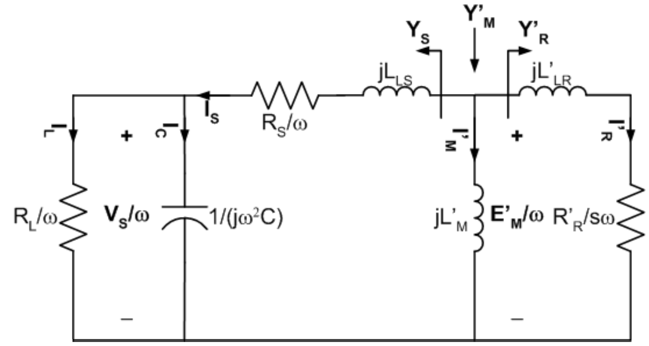


Fig. 2. Per phase equivalent circuit under self-excitation.

- An infinite bus and a long line connecting the wind turbine to the substation.
- A transformer at the pad mount
- Capacitors connected in the low voltage side of the transformer
- An induction generator

For the self-excitation, we focused on the turbine and the capacitor compensation only (the right half of Figure 1). For harmonic analysis, we considered the entire network shown in Figure 1.

III. Self-Excitation

A. The Nature of Self-Excitation in an Induction Generator

Self-excitation can occur in a fixed-speed wind turbine equipped with an induction generator. Fixed capacitors are the most commonly used method of reactive power compensation in a fixed-speed wind turbine. Induction generators alone cannot self excite. It requires reactive power from the grid to operate normally. The grid dictates the voltage and frequency of the induction generator.

Although self-excitation does not occur during normal grid-connected operation, it can occur during off-grid operation. For example, if a wind turbine operating in normal mode becomes disconnected from the power line due to a sudden fault or disturbance in the line feeder, the capacitors connected to the induction generator will provide reactive power compensation. However, the voltage and the frequency are determined by the balancing of the systems.

One disadvantage to self-excitation is the safety aspect. Because the generator is still generating voltage, it may compromise the safety of the personnel inspecting or repairing the line or generator. Another disadvantage is that the generator's operating voltage and frequency are determined by the balance between the system's real power and the reactive power. Thus, if sensitive equipment is connected to the generator during self-excitation, the equipment may be subjected to over/under voltage and over/under frequency operation. In spite of the disadvantages of operating the induction generator in self-excitation, some people use self-excitation for dynamic braking to help control the rotor speed during an emergency such as a grid loss condition. Thus, with the proper choice of capacitance and resistor load (to dump the energy from the wind turbine), the wind turbine can be brought to a safe operating speed during grid loss and mechanical brake malfunctions.

In an isolated operation, the conservation of real and reactive power must be preserved. The equation governing the system can be simplified by looking at the impedance or admittance of the induction machine. To operate in an isolated fashion, the total admittance of the induction machine and the rest of the connected load must be zero. The voltage of the system is determined by the flux and frequency of the system. Thus, it is easier to start the analysis from a node at one end of the magnetizing branch. Note that the term "impedance" in this paper is the conventional impedance divided by the frequency. The term "admittance" in this paper corresponds to the actual admittance multiplied by the frequency.

B. Steady-State Representation

Figure 2 shows an equivalent circuit of a capacitor-compensated induction generator. The principle of excitation for the parallel-compensated system is the same as in the series compensation. That is, the balance of real and reactive power must be maintained. Equation 1 gives the total admittance of the system:

$$Y_s + Y_m^{'} + Y_r^{'} = 0 \tag{1}$$

Equation 1 can be expanded into the equations for imaginary and real parts as shown in Equations 2 and 3.

$$\frac{\frac{R_1}{\omega}}{\left(\frac{R_1}{\omega}\right)^2 + L_1^2} + \frac{\frac{R_r'}{S\omega}}{\left(\frac{R_r'}{S\omega}\right)^2 + L_{lr}'^2} = 0 \tag{2}$$

$$\frac{1}{L_m'} + \frac{L_1}{\left(\frac{R_1}{\omega}\right)^2 + L_1^2} + \frac{L_{lr}'}{\left(\frac{R_r'}{S\omega}\right)^2 + L_{lr}'^2} = 0 \tag{3}$$

where:

$$R_1 = R_s + \frac{R_L}{(\omega C R_L)^2 + 1}$$

$$L_1 = L_{ls} - \frac{C R_L^2}{(\omega C R_L)^2 + 1}$$

One important characteristic needed to solve the self-excitation is the magnetizing characteristic of the induction generator. Figure 3 shows the relationship between the flux linkage and the magnetizing inductance, where an increase in the flux linkage increases the saturation level thus reducing the effective magnetizing inductance L_m. This graph can be derived from the no-load characteristic of the induction generator obtainable from the experiment.

To solve the above equations, we can set the capacitor (C) and the resistive load (R_L) values and then find the operating points for different frequencies. From Equation 2, we can find the operating slip at a particular frequency. Then, from Equation 3, we can find the corresponding magnetizing inductance L_m', and from here, we can find the operating flux linkage at this frequency (by using the L_m' vs flux linkage λ_m shown in Figure 3). The process is repeated for different frequencies.

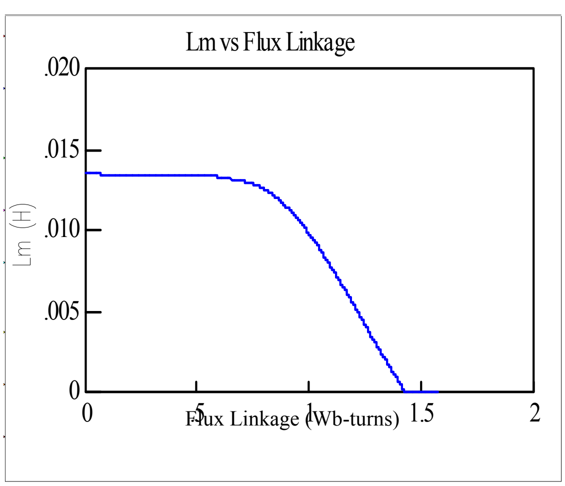


Fig. 3. The magnetization characteristic presented as L'_m versus λ_m.

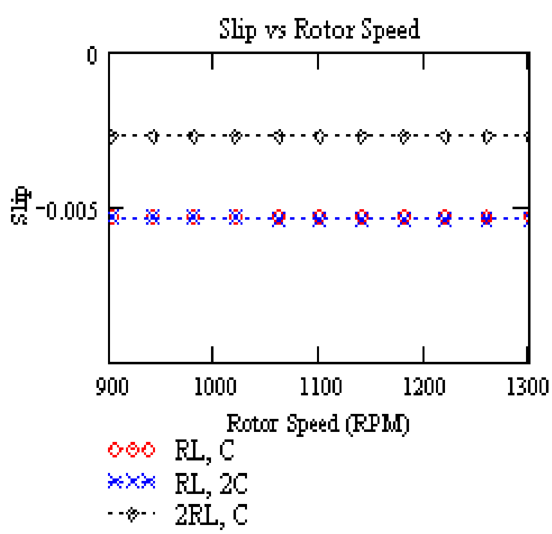


Fig. 4. The slip as a function of rotor speed for different R_L and C.

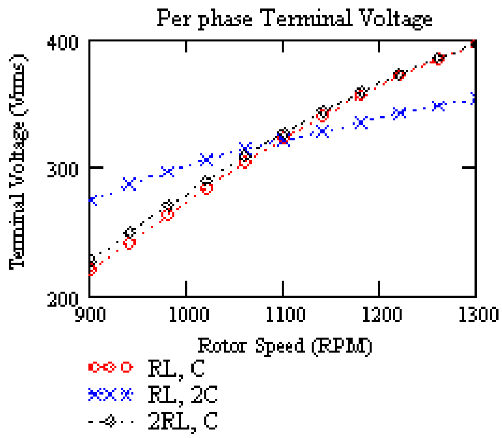


Fig. 5. Terminal voltage versus rotor speed for different R_L and C.

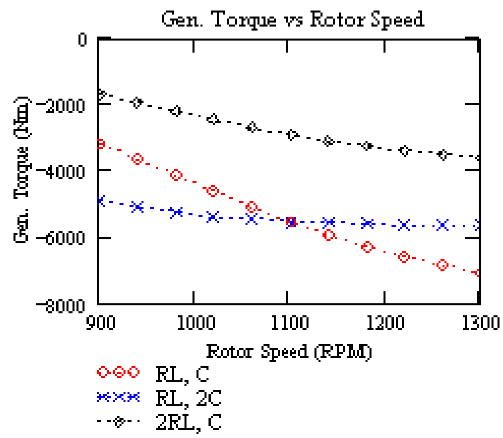


Fig. 6. The generator torque vs. rotor speed for different R_L and C.

As a base line, we consider a capacitor with a capacitance of 3.8 mF (milli-farad) connected to the generator to produce approximately rated VAR compensation for full load generation (high wind). The load resistance R_L = 1.0 ohm is used as the base line load. The slip versus rotor speed is presented in Figure 4. It shows that the slip is roughly constant throughout the speed range for a constant load resistance. The capacitance does not affect the operating slip for a constant load resistance. A higher resistance (R_L high = lower generated power) corresponds to a lower slip.

The voltage at the terminals of the induction generator (refer to Figure 5) can be computed to show the impact of the capacitance and load resistance. As shown above, the load resistance does not affect the terminal voltage, especially in the higher rpm (higher frequency). However, the capacitance has a significant impact on the voltage profile at the generator terminals. As shown, a larger capacitance gives a more constant voltage while a smaller capacitance makes the voltage increase as the rotor speed increases. This concept of self-excitation can be exploited to provide dynamic braking for a wind turbine to prevent the turbine from running away when it loses its connection to the grid. By choosing the correct values for capacitance and load resistance (or variable resistance), as shown in Figure 5, one can tailor the torque speed characteristic of the generator to provide dynamic braking during emergency shutdown when the turbine loses its connection to the grid.

Figure 6 shows that for the same capacitance, changing the effective value of the load resistance can modulate the torque-speed characteristic.

C. Dynamic Behavior

If an induction generator connected to a local grid, is a suddenly disconnected from that grid, the local load, the capacitor compensation, and the induction generator will operate in self-excitation mode. A short while later, the grid is reconnected to the wind turbine generator.

A value of 3.8 mF capacitance and a load resistance of 1.0 ohm was chosen for this simulation. The constant driving torque was set to be 4500 N.m. Note that the wind turbine characteristic is not included in this simulation, because we are more interested in the self-excitation process itself. Thus, we focused on the electrical side of the equations.

Figure 7 shows the rotor speed and the electrical output power. In this case, the induction generator is at zero speed when it is started. The speed increases until it reaches its rated speed. It is initially connected to the grid until t=3.1 seconds at which time the grid is disconnected and the induction generator operates in self-excitation mode. At t=6.375 seconds, the generator is reconnected to the grid, which terminates the self-excitation. The rotor speed increases slightly during self-excitation, but eventually, the generator torque matches the driving torque (4500 Nm), and the rotor speed is stabilized. When the generator is reconnected to the grid, there is a sudden brief change in the torque transient. This change occurs when the system is reconnected to the grid without any synchronization. When the induction generator is resynchronized with the grid, the rotor speed settles at the same speed as the rotor speed at $t < 3$ sec.

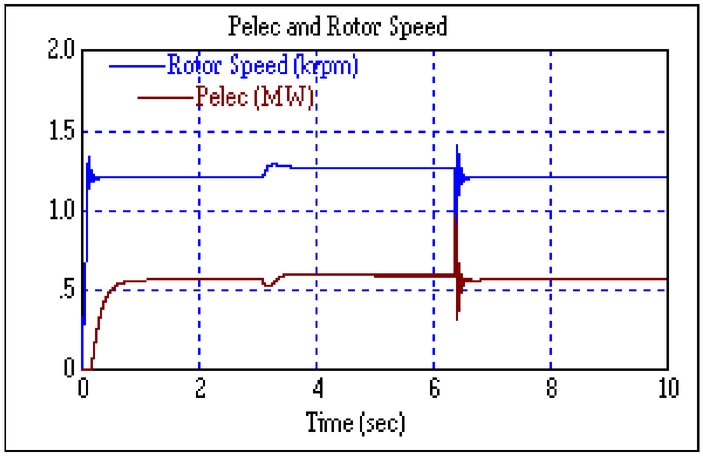


Fig. 7. The generator output power and rotor speed vs. time.

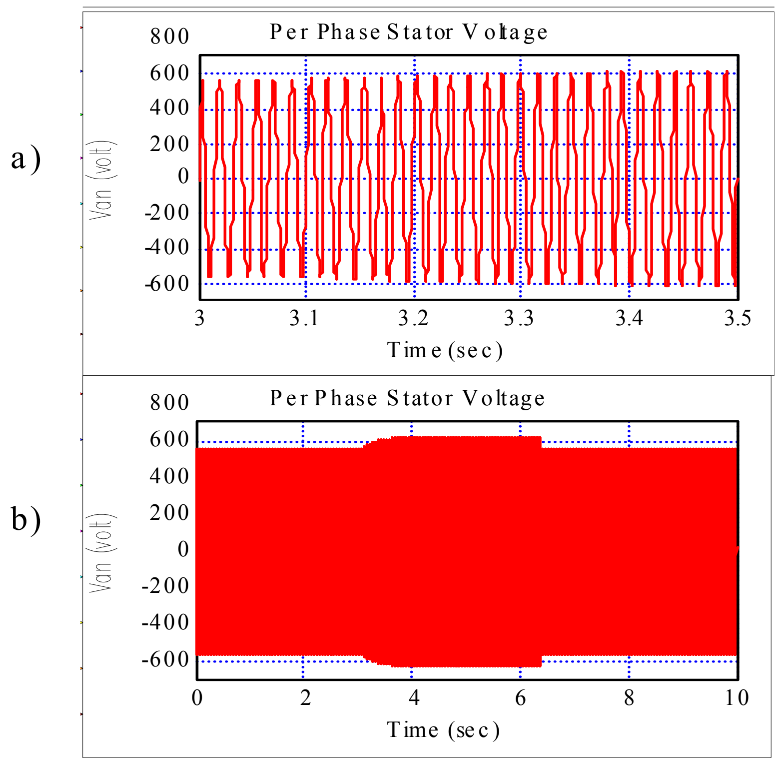


Fig. 8. The terminal voltage versus the time
a) the voltage and frequency are shown to vary
b) before, during self-excitation, and after reconnection.

Figure 8 shows the trace of per phase stator voltage. It shows that the stator voltage is originally the same as the grid voltage to which it is connected. During the self-excitation mode (3.1s < t < 6.375s), the voltage increases and the frequency is a bit higher than 60 Hz. The frequency then returns to its rated voltage when the induction generator is reconnected to the grid.

To observe the change in voltage during transient, the above graph is zoomed between t=3.0s to t=3.5 s. Note, that the frequency and voltage increase during self-excitation.

IV. Harmonic Analysis

A. Simplified Per Phase Higher Harmonics Representation

We replaced the power network shown in Figure 1, with a per phase equivalent circuit. In this circuit representation, the harmonics is denoted with h to indicate the higher harmonics multiples of 60 Hz. Thus h=5 indicates the fifth harmonics (300 Hz). In wind turbine applications, the induction generator, transformer, and capacitors are three phases and either Wye or Delta is connected. Thus, the flow of even harmonics, the third, and its multiples do not exist (only h = 5, 7, 11, 13, 17 . . . etc.).

1. Infinite Bus and Line Feeder

The infinite bus and the line feeder connecting the wind turbine to the substation are represented by a simple Thevenin representation of the larger power system network. Thus, we consider a simple RL line rep.

2. Transformer

We considered a three-phase transformer with standard impedance of 6%. Because the magnetizing inductance of a large transformer is usually very large compared to the leakage inductance, only the leakage inductance will be considered. Assuming the efficiency of the transformer is about 98% at full load, and the copper loss is equal to the core loss (general assumption for an efficient, large transformer), we can approximate the winding resistance, which is generally very small for an efficient, large transformer.

3. Capacitor Compensation

The capacitors representing the compensation of the wind turbine are switched capacitors. Although the manufacturer equipped the wind turbine with only 400 kVAR of reactive power compensation, the wind turbine we considered is equipped with an additional 1.5 MVAR reactive power compensation. The wind turbine is compensated at different levels of compensation depending on the level of generation. The capacitor is represented by the capacitance C. In series with the capacitance, is the parasitic resistance (R_c), representing the losses in the capacitor. This resistor is usually very small for a good quality capacitor.

4. Induction Generator

The induction generator (1.5 MW, 480V, 60 Hz) used for this wind turbine can be represented as the per phase equivalent circuit shown. Figure 8, shows the equivalent circuit of the induction generator. The operating slip of the generator at fundamental frequency (60Hz) is around 1%. The slip of induction generator at harmonic frequency can be computed as:

$$S_h = \frac{h\omega_s - \omega_r}{h\omega_s} \tag{4}$$

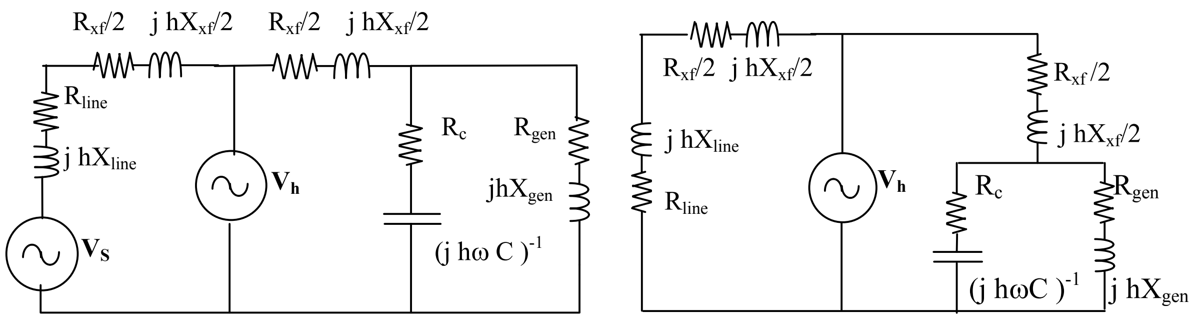
where

S_h = slip for h^{th} harmonics
h = harmonics order
ω_s = synchronous speed of the generator
ω_r = rotor speed of the generator

Thus for higher harmonics (5^{th} and higher) the slip is close to one (S_h = 1) and for practical purposes is assumed to be one.

B. Steady State Analysis

Figure 9 shows the simplified equivalent circuit of the interconnected system representing higher harmonics. Note that the magnetizing inductance of the transformers and the induction generator are assumed to be much larger than the leakages and are not included for high harmonic calculation. From the superposition theorem, we can analyze a circuit with only one source at a time while the other sources are turned off. For harmonics analysis, the fundamental frequency voltage source can be turned off. In this case, the fundamental frequency voltage source (infinite bus), V_s, is short-circuited. Based on the parameters given, we can use a steady-state analysis based on the simplified equivalent circuit shown in Figure 9.



(a) Complete Representation **(b) Harmonic Representation**

Fig. 9. The per phase equivalent circuit of the simplified model for harmonic analysis.

Wind farm operator experience shows us that harmonics occur when the transformer operates in the saturation region. Thus, the transformer operates at a higher flux causing the non-linearity of the magnetizing inductance $L`_m$ of the transformer. During the operation in this saturation region, the resulting current can be distorted so that we can see a sharply peaked sinusoidal current due to larger magnetizing current imbedded in the primary current. This non-sinusoidal current can excite the harmonics when the power network and the capacitor compensations hit its resonance frequency.

From the circuit diagram we can compute the impedance seen by the harmonic source as:

$$Z\left(C,h\right) = \left(Z_{line} + 0.5\ Z_{xfmr}\right) // \left(0.5\ Z_{xfmr} + Z_C//Z_{gen}\right) \qquad (5)$$

The admittance can be found from the impedance.

$$Z\left(C,h\right) = \frac{1}{Z\left(C,h\right)} \qquad (6)$$

The admittance corresponds to the corresponding harmonic current for a given harmonic voltage excitation. In this section, we analyze the system admittance from the most dominant harmonic frequency (up to 23^{rd} harmonics, excluding even and multiples third harmonics) and vary the size of the capacitor compensation. Because the data in the field only consists of the total harmonic distortion, and does not provide information about individual harmonics, we can only compare the trends shown by the admittance from the admittance calculation shown in Equations 5 and 6 to the measured data. Figure 10a shows the total admittance computed from equation 6 for all higher harmonics of interest up to 23^{rd} harmonics (odd and non-triplen harmonics) are plotted as a function of the total reactive power

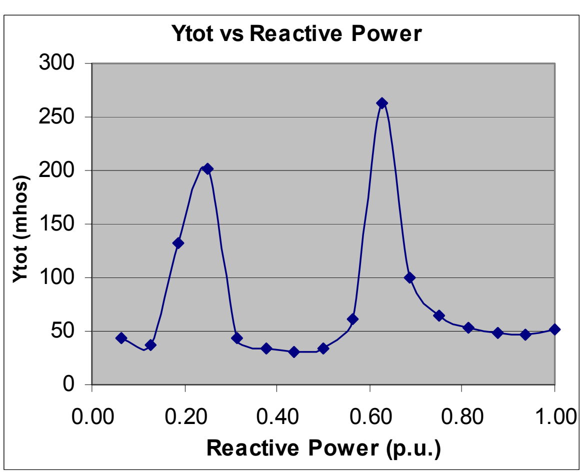


Fig. 10a. The total admittance for higher harmonics (odd and non-triplen) as a function of reactive compensation.

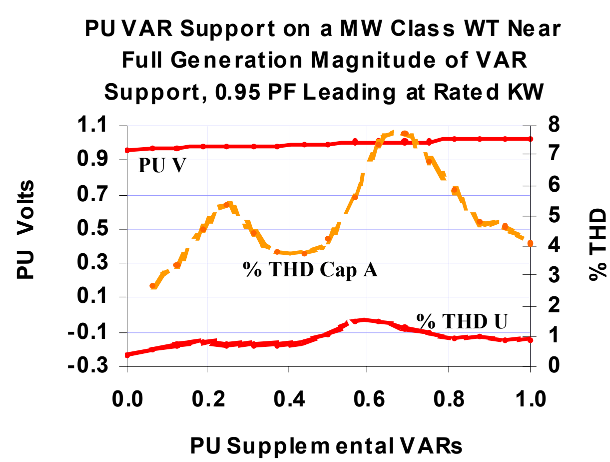


Figure 10b. Total harmonic distortion of the current as a function of the reactive compensation in per unit.

[in per unit] as the size of switched capacitors varied. For a comparison, the measured data of the total harmonic distortion as a function of the total reactive power (in per unit) is presented in Figure 10b. It is shown in both Figure 10a and Figure 10b that when the size of the capacitor compensation is increased, the circuit admittance (in Figure 10a) or the total harmonic distortion (in Figure 10b) shows resonance at different higher harmonics. The two graphs show the same trend. There are two values of capacitances that amplify the total harmonic distortions revealed from the calculation and from the field measurement. Although the magnitudes do not match completely, the size of reactive power at which the two resonance frequencies occur shows a good correlation between the field measurement and the calculated values.

From Figure 10, we can say that the circuit will resonate at different higher harmonics when that particular harmonics presents or excites the circuit.

C. Dynamic Simulation

In this section, we want to show how the harmonic sources are generated in the transformer. When a certain harmonic source is present, and the circuit presents a resonance circuit to the harmonic source, there will be a harmonic current flowing in the network. From the previous section, we learned that the wind turbine is compensated by increasing the reactive power as the generated power increases. Different sizes of capacitors that are connected to the power system network can lead to different resonance frequencies.

Most utility-size wind turbines are equipped with a pad-mount step-up transformer that connects them to the utility. In this section, we will show the nature of a transformer that can lead to producing current harmonics in the circuit. The non-linear characteristic of the magnetic circuit in the transformer shows that a non-sinusoidal current is generated when the transformer saturated. This non-sinusoidal current can excite the power system circuit.

Figure 11 shows the per-phase equivalent circuit of a transformer. The iron core loss of a transformer is usually represented as a parallel resistance, $R'_{C,}$ commonly found in a per-phase equivalent circuit. In this study, the core loss is neglected, and the equivalent resistance, $R'_{C,}$ is eliminated from the equivalent circuit. The magnetizing flux linkage is proportional to the ratio of the voltage and the frequency.

$$\lambda_M \approx \frac{|E_M|}{\omega_B} \tag{7}$$

where

E'_M = the magnetizing voltage

λ_M = flux linkage

ω_B = the base angular frequency

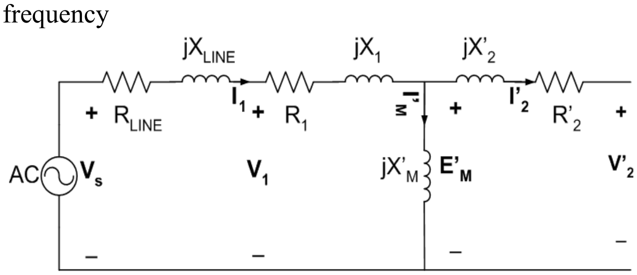


Fig.11. Per-phase equivalent circuit of a transformer.

Figure 12 shows the relationship between the voltage and current when the transformer is operated under saturation. The flux linkage of the transformer can be found from equation 6. The relationship between the flux linkage and the exciting current I'_M magnetizing inductance L'_M is non-linear. When the exciting current is low, the flux (and flux linkage) varies linearly, but eventually the saturation is reached, and the non-linear characteristic starts. A further increase in exciting current I'_M, will produce a smaller increase in the flux linkage. In the saturation region, the exciting current I'_M will be non-sinusoidal due to the non-linearity of the magnetizing inductance. Figure 12 shows the resulting current to be non-sinusoidal. This non-sinusoidal current can be displayed on the oscilloscope, and it can be measured by using a power quality meter to measure harmonic contents of the current.

There are two types of operation that can affect the nonlinear current ($I`_{M)}$. The first one occurs when the transformer operates in a higher voltage level thus driving the operation in to the saturation region. This can happen when the voltage across E'_M is high. One example of this operation is when the transformer is lightly loaded, thus the voltage drop across the line feeder and the primary-winding impedance is small. Thus the magnetizing branch is

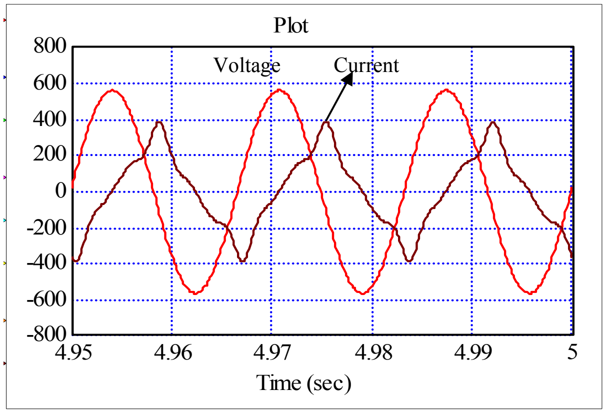


Fig.12. The voltage and current of a transformer under light load condition.

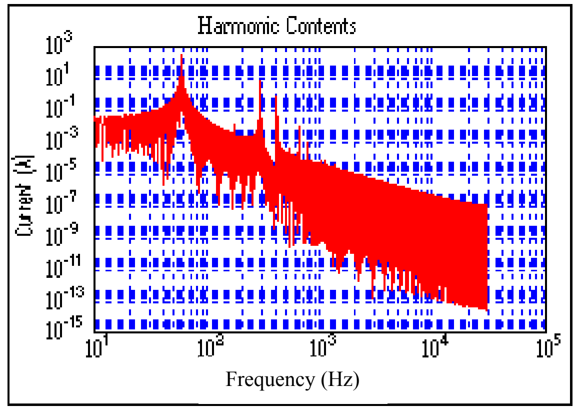


Figure 13. Harmonic content of the distorted light load current.

exposed to a high voltage E`$_M$ producing a large magnetizing current I'$_M$ in the magnetizing branch. Another example of operation that can result in the high saturation is when the transformer is operated with a leading power factor. The voltage across the magnetizing branch can be expressed as:

$$E'_M = V_S - I_1 \left(Z_{LINE} + Z_1\right) \quad (8)$$

When the current I_1 is small and/or leading, the corresponding E'$_M$ will be closer or higher than V_S, and, if the voltage V_S is high to begin with, the transformer will operate in a saturation region. Under normal operation, the current I_1 is at rated current, thus there is a sufficient voltage drop across Z_1 and Z_{LINE}, and the voltage E'$_M$ will be at its rated voltage (linear region).

The resulting current for operation under saturation is a distorted current waveform as shown in Figure 12. The distorted portion of the current shows that the operating point moves into a non-linear saturation region. The harmonic contents of the current can be observed from the frequency spectrum shown in Figure 13. As can be expected, for a three phase balanced system, the even and third multiples harmonics do not exist. As a comparison, the current of the transformer under a loaded condition is shown in Figure 14. It is obvious that the voltage drops across the leakage reactance and the winding resistance keep the voltage across the magnetizing branch from becoming excessively high, thus the operation of the transformer is in the linear region.

Another factor that can affect the transformer saturation is the tap changer. A tap changer is a device fitted into a transformer programmed to change the turn-ratio or the number of turns of the transformer on-line. The purpose of the tap changer is to control the voltage on the customer side to be as constant as possible. With an increase in the effective number of turns of the transformer, the magnetizing inductance L'$_M$ will increase accordingly (proportional to the square of the number of turns). It means that for the same voltage E`$_M$, we get the less exciting current I'$_M$. With the less exciting current, we operate the transformer in a less saturate condition (closer to linear region). In

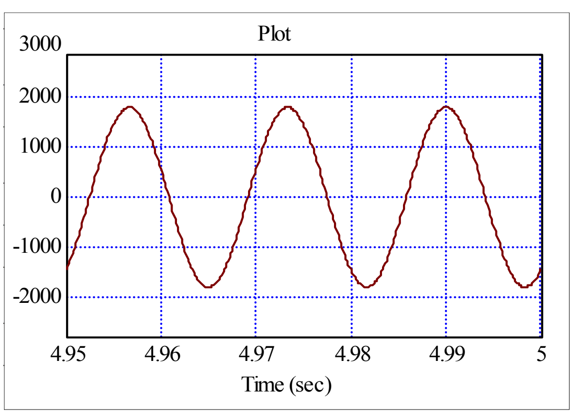


Figure 14. Sinusoidal Current of a Transformer under Loaded Condition.

essence, we can avoid the non-linear region completely if we have enough room to change the tap on the transformer.

For a comparison between unsaturated and saturated conditions, we can compare the current shown in Figure 12 (saturated, light load condition) to the current shown in Figure 14 (unsaturated, loaded condition). The current distortions due to saturation as shown in Figure 12 do not show up when the transformer is loaded (unsaturated) as shown in Figure 14.

V. Conclusion

This paper presents the nature of self-excitation and harmonics generated by a fixed-speed induction generator commonly used in wind turbine generation. Although neither self-excitation nor harmonics are desired outcomes of electricity generated by wind turbines, without proper design and control, either may occur.

In self-excitation, the operator is concerned about the safety of personnel repairing the line. However, self-excitation can be used for dynamic braking to keep the wind turbine from running away as well as for other applications. The size of dynamic resistor and capacitor installed must be pre-calculated to ensure the desired result.

The saturation of the magnetic circuit in the transformer and the resonance circuit between the capacitor compensation and the rest of the circuit can make the power system susceptible to harmonic flows. Although the power network stays the same, the resonance occurs at several different frequencies because the capacitors change sizes as the wind speed increases. The source of harmonics is generated in the magnetizing branch due to magnetic saturation of the iron core. The tap changer, the power factor, and the level of generation of the wind turbine affect the level of saturation, and thus, the nature of the harmonic source.

Acknowledgments

We acknowledge the support of the U.S. Department of Energy and we also thank Jorge Chacon from Southern California Edison for his help and discussions.

References

1. Sallan, J., Muljadi, E., Sanz, M., Butterfield, C.P.; "Control of Self-Excited Induction Generators Driven by Wind Turbines." *8th European Conference on Power Electronics and Applications Conference (EPE99) in Lausanne (Switzerland), 7-9 September 1999*.
2. Tang, L. Zavadil, R.M., Smith, J.C., Childs, S.; "Parametric Study of the Performance of a Passive Dynamic Brake." *Windpower '91 Conference Proceedings, Palm Spring, CA, Sept. 24-27, 1991*, pp. 273-280.
3. Krause, P.C.; *Analysis of Electric Machinery*, McGraw Hill Book Company, 1986.
4. Fitzgerald, A.E., Kingsley, C. Jr., Uman, S.D; *Electric Machinery*, Sixth Edition, McGraw Hill Book Company, 2003.
5. Neves, W., Dommel, H., "Saturation Curve of Delta-Connected Transformer from Measurements," *IEEE Transactions on Power Delivery*, Vol. 10, Issue: 3, July 1995, pp. 1432-1437.
6. *VisSim/Simulink Translator User's Guide-Version 5,* Visual Solutions, Inc., 2002.
7. *MathCad User's Guide with Reference Manual*, MathSoft Inc., 2001.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
November 2004	Conference Paper	January, 12-13 2005

4. TITLE AND SUBTITLE
Self Excitation and Harmonics in Wind Power Generation: Preprint

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
E. Muljadi, C.P. Butterfield, H. Romanowitz, and R. Yinger

5d. PROJECT NUMBER
NREL/CP-500-33138

5e. TASK NUMBER
WER5-3108

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
H. Romanowitz: Oak Creek Energy Systems, Inc.
R. Yinger: Southern California Edison

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/CP-500-33138

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES
NREL Technical Monitor:

14. ABSTRACT *(Maximum 200 Words)*
Traditional wind turbines are equipped with induction generators. Induction generators are preferred because they are inexpensive, rugged, and require very little maintenance. Unfortunately, induction generators require reactive power from the grid to operate. Because reactive power varies with the output power, the terminal voltage at the generator may become too low to compensate the induction generator. The interactions among the wind turbine, the power network, and the capacitor compensation, are important aspects of wind generation. In this paper, we will show the interactions among the induction generator, capacitor compensation, power system network, and magnetic saturations and examine the cause of resonance conditions and self-excitation.

15. SUBJECT TERMS
Wind turbine; induction generator; capacitor compensation; wind energy

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	UL		19b. TELEPONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1146-E(05/2004)