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TRANSIENT RESPONSE OF WOUND ROTOR INDUCTION MACHINE DURING BALANCE THREE PHASE VOLTAGE SAG

Sanjay J. Patel

Lecturer in Electrical Engineering, Govt. Polytechnic- Jamnagar.- Gujarat (India)

ABSTRACT -The use of wound rotor induction machine has become very popular in wind power generation since last many years. The WRIM can generate power at variable speed and are operated with converters whose rating is only fraction of wind turbine rating. The main drawback of WRIM based wind turbine is that it is very sensitive during grid disturbance particularly for the voltage sags. As the WRIMs are widely used in wind power generation, the transient response of the WRIM during grid disturbance has been investigated extensively in recent year. The main focus of this paper is to analyse the transient response of WRIM under balanced voltage sag from the theoretically. The result of this analysis helps to understand the problem of existing system and provides very useful tools to solve the existing problem and to improve new propose control as well as strategies.

KEYWORDS : Wound rotor induction machine, voltage sag, rotor induced emf, forced flux, natural flux.

NOMELCLATURE

R_s, R_r	Stator, rotor resistance
L_s, L_r	Stator, rotor self inductance
L_m	Magnetizing inductance
ω_e	Synchronous angular frequency
ω_r	Rotor electrical angular frequency
ω_s	Slip angular frequency
s	Slip

1.INTRODUCTION

Recently, the wind energy is considered as a best alternative to the conventional energy sources such as gas oil or coal etc, for the generation of electricity. Among various types of wind turbines , the wind turbine based on wound rotor induction machine has become popular because of variable speed operation and fraction scale power electronic converters [1].

In wind power generation, the stator winding of wound rotor induction machine is directly connected to the grid, whereas its rotor winding also connected to the grid via back to back converter as shown in figure1. With help of back to back converter in the rotor side, the WRIM can be made to generate electricity at both below as well as above-synchronous speed [2].

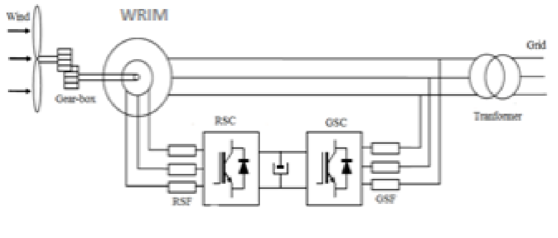

Figure 1: electrical Configuration of WRIM in wind power generation

The grid voltage oriented vector control technique is used for grid side converter to maintain the dc-link voltage constant irrespective of direction and magnitude of power flow and control the reactive power exchange with the grid. A vector control technique is also used for the rotor side converter, which is responsible for tracking of maximum power and controls the reactive power exchange with the grid [3].

The main disadvantages of WRIM based wind turbine is that it is very sensitive during the grid disturbance particularly for the voltage sags. Due to the abrupt sag of the grid voltage ,there may be an over voltage and over currents in the rotor winding that could damage the back to back converter if no protection device is employed [4],[5]. Moreover, the voltage sag will cause an efficiency penalty due to the twice grid frequency heating of the dc-link capacitors [7]. At first, the solution implemented by the manufactures to protect the converter was to short circuit the rotor windings via crowbar and disconnect machine from the grid. Therefore wind turbine is not able to support in resuming normal operation of grid.

As the WRIMs are broadly used in wind power generation, the transient response of WRIM during the grid voltage sag has been investigated extensively in recent year. This paper represents analysis based on transient response of WRIM during balanced voltage sag, from the theoretically. The paper is organized as follows. Section II shows equivalent circuit of WRIM in stationary reference frame. Section III shows the performance under normal operating condition. Section IV shows the performance during full voltage sag. Section V shows the performance during fraction balanced voltage sag. Section VI shows the simulation circuit and its waveforms Section VII gives the conclusion of this theoretical based analysis.

2. EUIVALENT CIRCUIT OF WRIM

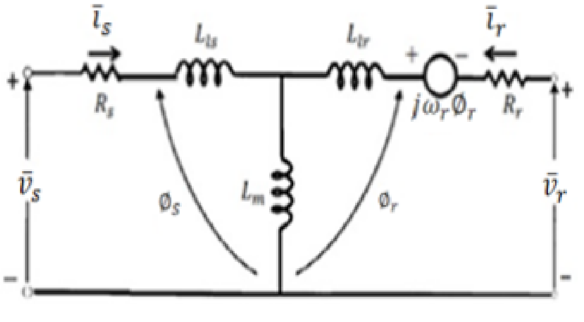

Figure 2: Equivalent circuit of WRIM in stationary reference frame

The synchronously rotating reference frame are most commonly used for the analysis of A.C. electrical machine because all the sinusoidal variables in the stationary reference frame appear as dc variables in synchronously rotating reference frame [8]. However, for the understanding the performance of WRIM under grid disturbances theoretically, the stationary reference frame is most appropriate. The equivalent circuit of WRIM in the stationary reference frame is shown in figure 2. The stator and rotor voltage can be expressed

$$\bar{v}_s = R_s\bar{i}_s + p\bar{\emptyset}_s \tag{1}$$

$$\bar{v}_r = R_r\bar{i}_r + p\bar{\emptyset}_r - \omega_r\bar{\emptyset}_r \tag{2}$$

Where, $\emptyset_s = L_S\bar{i}_s + L_m\bar{i}_r$ (3)

$$\bar{\emptyset}_r = L_r\bar{i}_r + L_m\bar{i}_s \tag{4}$$

By multiplying equation (3) by L_m, we get

$$L_m\bar{\emptyset}_s = L_mL_s\bar{i}_s + L_m^2\bar{i}_r \tag{5}$$

By multiplying equation (4) by L_s, we get

$$L_s\bar{\emptyset}_r = L_sL_r\bar{i}_r + L_sL_m\bar{i}_s \tag{6}$$

The subtraction of (5) from (6) yield:

$$\bar{\emptyset}_r = \frac{L_m}{L_s}\bar{\emptyset}_s + L_r\left[1 - \frac{L_m^2}{L_sL_r}\right]\bar{i}_r$$

$$\therefore \quad \bar{\emptyset}_r = \frac{L_m}{L_s}\emptyset_s + \sigma L_r\bar{i}_r \tag{7}$$

Where, $\sigma = 1 - \frac{L_m^2}{L_sL_r}$

Where σ is known as the flux leakage factor and σL_r is known as the rotor transient inductance

By substituting the value of $\bar{\emptyset}_r$ from (7) into (2), we get

$$\bar{v}_r = R_r\bar{i}_r + p\left[\frac{L_m}{L_s}\bar{\emptyset}_s + \sigma L_r\bar{i}_r\right] - j\omega_r\left[\frac{L_m}{L_s}\bar{\emptyset}_s + \sigma L_r\bar{i}_r\right]$$

$$\therefore \ \bar{v}_r = \frac{L_m}{L_s}[p - j\omega_r]\bar{\emptyset}_s + [R_r + \sigma L_r(p - j\omega_r)\bar{i}_r] \tag{8}$$

The equation (8) consists is made of two parts. The first part of (8) is corresponding to the emf induced in the rotor by stator flux and it is known as open circuit rotor voltage which is one of most important quantity for the rotor side converter. It is expressed by an equation.

$$\bar{e}_r = \frac{L_m}{L_s}[p - j\omega_r]\bar{\emptyset}_s \tag{9}$$

The second part of equation (8) comes in picture only when there is a flow of current in the rotor winding. and it is due to the voltage drop across the resistance arR_rd the rotor transient inductance σL_r.

III. PERFORMANCE OF WRIM UNDER NORMAL OPERATING CONDITION.

In wind power generation, the stator winding of wound rotor induction machine is directly connected to the grid, whereas its rotor winding also connected to the grid via back to back converter. It means that the stator winding are supplied from constant voltage constant frequency three phase AC power source and the rotor winding are supplied through a power electronic converter that is able to supply the WRIM with variable voltage variable frequency three phase AC power source.

During the normal condition of the grid, the stator voltage is a rotating vector, whose amplitude is equal to the grid voltage

$$\bar{v}_s = v_g e^{j\omega_e t} \tag{10}$$

If the stator resistance is neglected, then from (1), we get

$$\bar{\emptyset}_s = \int \bar{v}_s \ dt$$

$$\therefore \ \bar{\emptyset}_s = \int v_g e^{j\omega_e t} \ dt$$

$$\therefore \ \bar{\emptyset}_s = \frac{v_g}{j\omega_e} e^{j\omega_e t}$$

$$\therefore \ \bar{\emptyset}_s = \emptyset_s e^{\omega_e t} \tag{11}$$

Where, $\emptyset_s = \frac{v_g}{j\omega_e}$

From the above mathematical analysis it is clear that during normal condition of the grid, the stator flux is rotating at the synchronous speed and its amplitude is constant and proportional to the grid voltage. Thus the rate of change of the stator flux links with rotor winding is proportional to slip speed i.e. (synchronous speed - rotor speed) and so the magnitude and frequency of rotor induced emf is proportional to slip. As the WRIM are typically operated with the slip in the range of -30% to +30% so the magnitude and frequency of rotor induced emf is relatively low. Such a rotor induced emf should be predominantly balanced by voltage injected by converter at same frequency and thus it determines the voltage rating of rotor side converter with some suitable margin.

The rotor induced emf during normal operation is obtained substituting (11) into (9):

$$\bar{e}_r = \frac{L_m}{L_s}[p - j\omega_r]\emptyset_s e^{j\omega_e t}$$

$$\therefore \ \bar{e}_r = \frac{L_m}{L_s}[j\omega_e - j\omega_r]\emptyset_s e^{j\omega_e t}$$

$$\therefore \ \bar{e}_r = j\frac{L_m}{L_s}[\omega_e - \omega_r]\frac{v_g}{j\omega_e} e^{j\omega_e t}$$

$$\therefore \ \bar{e}_r = s\left[\frac{L_m}{L_s}\right]v_g e^{j\omega_e t} \tag{12}$$

The magnitude of rotor induced emf during normal operating condition is given by

$$e_r = s\left[\frac{L_m}{L_s}\right]v_g \tag{13}$$

IV .PERFORMANCE OF WRIM DURING FULL VOLTAGE SAG

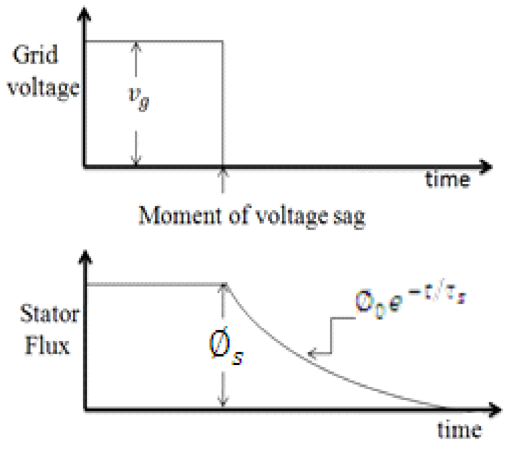

Figure 3: variation in stator flux during full voltage sag

During full voltage sag, the voltage at the stator terminal goes down to zero value. As flux is state variable, it cannot have any discontinuity. Therefore the stator flux cannot reduce to zero value immediately even if the grid voltage is reduced to zero value. But the stator flux can reduced from its initial value to zero value exponentially as per R-L time constant of stato τ_s as shown in figure 3. The initial value of stator flux during voltage sag is according to grid voltage just before voltage sag. Thus at first moment of voltage sag, the magnitude of stator flux is equal to that of just before voltage sag. One more important characteristic of the stator flux during voltage sag is that it does not rotate, but it is static with respect to the stator.

Hence during full voltage sag, the rate of change of stator flux links with rotor winding is proportional to speed of rotor. As the rotor speed is much more than slip speed, so magnitude and frequency of rotor induced emf at first moment of voltage sag is very high. As the WRIM are typically operated with the slip in the range of -30% to +30%the magnitude of rotor induced emf is about 3.5 to 6.5 time that induced during normal operation and the frequency of rotor induced emf is about 35 Hz to 65 Hz depending upon the value of slip. Such high rotor induced emf saturates the converter and there is a loss of rotor current control and so over current may results. With the passage of time, magnitude and frequency of rotor induced emf decreases exponentially with decreases in the stator flux.

The stator flux during full voltage sag is given by

$$\emptyset_s = \overline{\emptyset}_0 e^{-t/\tau_s} \qquad (14)$$

Where, $\overline{\emptyset}_0 = \frac{v_g}{j\omega_e}$ And $\tau_s = \frac{L_s}{R_s}$

The rotor induced emf during full voltage sag is obtained by substituting (14) into (9)

$$\bar{e}_r = \frac{L_m}{L_s}[p - j\omega_r]\overline{\emptyset}_0 e^{-t/\tau_s}$$

$$\therefore \bar{e}_r = -\frac{L_m}{L_s}\left[\frac{1}{\tau_s} + j\omega_r\right]\overline{\emptyset}_0 e^{-t/\tau_s} \qquad (15)$$

The magnitude of rotor induced emf at first moment of full voltage sag is given by

$$e_{r(t_0)} \cong \frac{L_m}{L_s}\frac{\omega_r}{\omega_e}v_g$$

$$\therefore e_{r(t_0)} \cong \frac{L_m}{L_s}(1-s)v_g \qquad (16)$$

V .PERFORMANCE OF WRIM DURING FRACTIONAL BALANCED VOLTAGE SAG.

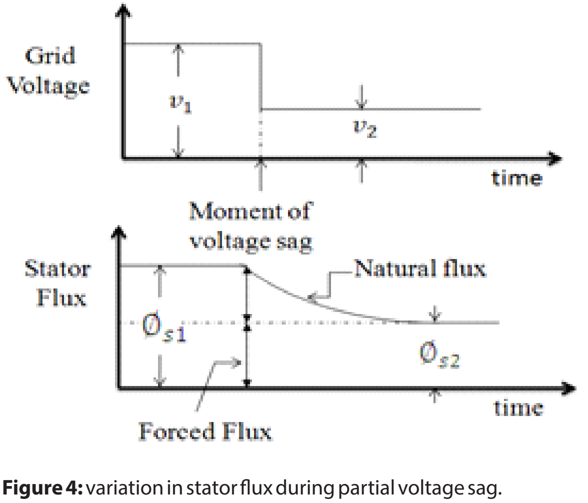

Figure 4: variation in stator flux during partial voltage sag.

Suppose that the grid voltage is changes from one voltage level to another voltage level as shown in fig 4, the stator flux cannot be change from one steady state level λ_{s1} o another steady state level λ_{s2} instantaneously, but it decrease exponentially as per R-L time constant of stator as shown in figure 4. Thus during partial voltage sag, the stator flux can be decomposed into two parts: One according to new grid voltage v_2 (it is called forced flux) and other according to depth of voltage sag $(v_1 - v_2)$ (it is called natural flux).

The forced flux rotates at synchronous speed and its magnitude is constant and proportional to new grid voltage. The natural flux is static with respect to the stator and its magnitude decrease exponentially as per R-L time constant of stator and its initial magnitude depends upon the depth of voltage sag. Thus the rate of change of forced flux links with rotor is proportional to the slip speed but, the rate of change of natural flux links with rotor is proportional to rotor speed. Thus during first moment of fractional voltage sag, emf of high amplitude and high frequency are induced in rotor only due to the natural flux. With the passage of time natural flux decay and so rotor induced emf of high frequency due to natural flux does not remains as long and only rotor induced emf of low frequency due to forced flux still remains

If the depth of the voltage sag is small, the emf induced in rotor does not exceeds the maximum voltage that converter can generates and so rotor current remains within the controllable limits. But for larger voltage sag, the emf induced in rotor exceeds the voltage rating of converter and so rotor current does not remains within the controllable limits and so over current will occurs.

The stator flux during voltage sag of depth k is given by

$$\overline{\emptyset}_s = \frac{(1-k)v_g}{j\omega_e}e^{\omega_e t} + \frac{kv_g}{j\omega_e}e^{-t/\tau_s} \qquad (17)$$

The first and second term of (17) gives the stator forced and natural flux respectively.

The rotor induced emf during voltage sag of depth k is obtained by substituting (17) into (9):

$$\bar{e}_r = \frac{L_m}{L_s}\left[s(1-k)v_g e^{j\omega_e t} - (1-s)kv_g e^{-t/\tau_s}\right] \qquad (18)$$

The magnitude of rotor induced emf at first moment of voltage sag is given by

$$e_{r(t0)} = \frac{L_m}{L_s}[s(1-k) + (1-s)k]v_g \qquad (19)$$

Here, first and second term of (19) represents the magnitude of rotor induced emf due to the stator forced and natural flux respectively.

VI. SIMULATION RESULTS

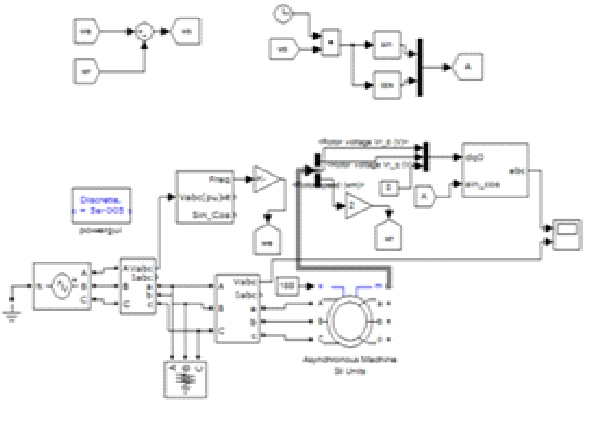

Figure 5: Simulation circuit

Figure 5 shows the simulation circuit for validation of the analysis discussed in previous section. Here the stator of WRIM is connected with programmable three phase voltage source and the machine is driven at constant speed. The parameter of WRIM used in simulation is given in appendix – I.

The variation in rotor induced emf during full as well as balanced partial voltage sag of 50 % with slip $s = -0.25$ is shown in figure 6 and 7 respectively. From the wave from, it is clear that before voltage sag the rotor induced emf is corresponding to slip speed and its peak value is about 50 volts and frequency is about 12.5 Hz.

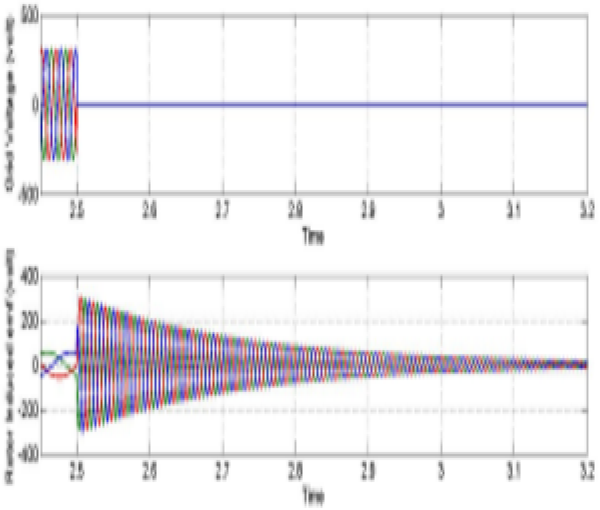

Figure 6: variation in rotor induce emf during full voltage sag

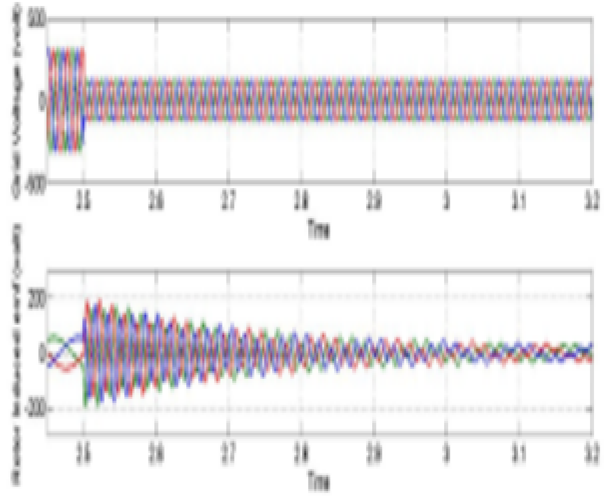

Fig 7: Variation in rotor induced emf during partial voltage sag.

During full voltage sag, the rotor induced emf due to natural flux is proportional to rotor speed whose magnitude is maximum at first moment of voltage sag and it is decay exponentially with natural flux. During full voltage sag, the peak value of rotor induced emf per phase is about 320 volts and its frequency is about 62.5 Hz.

The waveform of rotor induced emf during balanced fractional voltage sag is same as that of during full voltage sag at certain level but it is quite asymmetrical because of addition of two sinusoidal emf of different frequencies. At beginning of voltage sag, only sinusoidal emf of 62.5 Hz frequency corresponding to natural flux can be distinguished. With the passage of time, this component does not appears as long and only sinusoidal component of 12.5 Hz corresponding to forced flux is still remains. The peak value of rotor induced emf per phase during 50% balanced voltage sag is about 210 volts.

VII. CONCLUSION

The transient response analysis of WRIM during balanced voltage sag has been proposed. In this analysis during balanced voltage sag, the stator flux is decomposed in to two parts; the natural flux and forced flux. This analysis shows that the natural flux is only responsible for high magnitude and high frequency the rotor induced current during voltage sag, whose magnitude is maximum at first moment of voltage sag. If rotor side convertor does not balance this over voltage, the control of rotor current is lost which may causes rotor over current.

The analysis developed in this paper helps to understand the problem of existing system and provides very effective tools to solve the problem of existing system and to improve new propose control as well as protection strategies.

APPENDIX – I

Table 1: Parameter of WRIM

Parameter (Units)	Value
Rated Power (KW)	20
Stator Voltage (V)/ Frequency (Hz)	380/50
Stator / Rotor turns ratio	1
Stator resistance ()	170
Rotor Resistance ()	185
Stator Leakage Inductance (mH)	3.2
Rotor Leakage Inductance (mH)	3.2
Magnetizing Inductance (mH)	48.5
Number of Pole Pair	4

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