산업용 전력계통의 주파수 안정도와 전압 안정도를 고려한 부하차단 설계

論 文
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A Design of Load Shedding System Considering both Angular Stability and Voltage Stability in Industrial Power System

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Abstract - This paper has presented, taking an example of a gas separation plant, dynamic analysis on frequency decline caused by the over-loading at the generator and the knee point causing voltage instability due to reactive power required by re-acceleration of large induction motors, resulting in phenomena of failure in the conventional frequency load shedding. In order to resolve the voltage instability problem, a design of load shedding system employing under-voltage relays has been proposed to the industrial power system containing large induction motors in addition to the conventional load shedding employing frequency relays.
For the purpose of dynamic analysis, models of gas turbine and governor, synchronous generator, brushless exciter, and induction motor are introduced.

Key Words : load shedding system, voltage stability, frequency stability, industrial power system, induction motor

1. INTRODUCTION

Some severe disturbances in power systems can result in cascading outages and isolation of areas, causing formation of electrical islands. If such an islanded area is under-generated, it will experience a frequency decline. Unless sufficient generation with ability to rapidly increase output is available, the decline in frequency will be largely determined by frequency sensitive characteristic of loads. In many situations, the frequency decline may reach levels that could lead to tripping of turbine generating units by under frequency relays. To prevent extended operation of separated areas at lower than normal frequency, load shedding schemes are employed to reduce the connected load using frequency relays to a level that can be safely supplied by available generation.[1],[2]

The industrial power systems have usually in-house generators and import some amount of power through a utility tie. Major loads are induction motors in the systems. If the utility ties are lost, the power deficiency in the industrial systems will cause frequency decline, which can be restored by load shedding with frequency threshold and proper time setting. This load shedding scheme relies on frequency variation based on angular stability and has been so far adopted in the utility and industrial system.

The angular stability is basically concerned with the following swing equation.

$$\frac{d(-\Delta f)}{dt} = \frac{1}{2H}(\Delta P - D\Delta f) \quad (1)$$

$$\frac{d\delta}{dt} = \Delta f \quad (2)$$

where ΔP is over-load in per unit, Δf is frequency deviation in per unit.

However the load shedding scheme relying on frequency only can not completely resolve the power deficiency problem in the industrial power system which contains large induction motors. When a tie line is lost by a system fault, the transient voltage dip during the fault period causes re-acceleration of induction motors and voltage instability in case of excessive over-load in the power systems. This voltage instability can prevent the decline in frequency and result in failure of the frequency load shedding.

This paper presents dynamic analysis on frequency decline per over-load amount and the knee point causing voltage instability due to induction motors in the industrial power systems, taking an example of overseas gas separation plant.[3],[4]

2. MODELLING AND SIMULATION

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Voltage stability is classified into two categories: large disturbance voltage stability and small disturbance voltage stability. The large disturbance voltage stability is further subdivided into transient and long-term time frames. The voltage stability discussed in this paper belongs to the transient time frame, which is the same as that of rotor angle stability. This form of voltage instability can be analyzed by conventional transient stability simulation under appropriate models being used to represent the devices, particularly induction motors, various controls, and protections. [5]

2.1 Model for voltage stability analysis

The structure of the system model for voltage stability is similar to that for transient stability analysis. The overall system equations are comprised of a set of first-order differential equations and a set of algebraic equations in the following form.

$$\dot{\mathbf{X}} = f(\mathbf{x},\mathbf{V}) \tag{3}$$

$$\mathbf{I}(\mathbf{x},\mathbf{V}) = \mathbf{Y}_N\mathbf{V} \tag{4}$$

Initial conditions $(\mathbf{x}_0, \mathbf{V}_0)$ are known where

x : state vector of the system

V : bus voltage vector

I : current injection vector

$\mathbf{Y}_N$: network bus admittance matrix.

2.2. Models for transient stability analysis

2.2.1 Network System

The industrial power system employed for a sample study is that of a real gas separation plant in Thailand, which contains 9 bus comprising 1 swing bus, 2 generator bus, and load bus as well as branches comprising transformers and cables. The plant power system includes 115kV, 50Hz utility connection and its down stream radial systems such as 6.9kV, and 0.4kV systems. Generators are connected to 6.9kV bus. See figure 1 for the details.

2.2.2 Synchronous Machine

The transient model for a salient pole machine is used for generators.[6] The model uses an internal voltage source behind a fictitious impedance Rh+jXh. Rh and reactance Xh are used to replace Req and Xeq to achieve a faster convergence, i.e.:

$$Req = Rh = Ra \tag{5}$$

$$Xeq = Xh = Xa \tag{6}$$

where,

$$Rh + jXh = \frac{Ra^2 + Xd'Xq'}{Ra - j(Xd'Xq')/2}$$

This model is more comprehensive than the equivalent model because it includes more parameters to account for the machine's saliency.

$$Eh = Et + (Rh+jXh)\ It \tag{7}$$

$$\frac{dE'q}{dt} = \frac{1}{T'do}(Efd - Ei) \tag{8}$$

$$\frac{dE'd}{dt} = 0 \tag{9}$$

$$E'q = Ehq + (X'd - Xh)\ Id \tag{10}$$

$$E'd = 0 \tag{11}$$

$$Eq = Ehq + (Xd - Xh)\ Id \tag{12}$$

$$Ed = 0 \tag{13}$$

$$Ei = Eq + f\,(Eq) \tag{14}$$

The swing equation for the synchronous generator is as follows.

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(Pm - Pe - D\Delta\omega) \tag{15}$$

2.2.3. Excitation system

The excitation system of the generator is a brushless type, for which IEEE type 2 is employed as shown in the figure 3. [7]

2.2.4. Gas Turbine System

The simplified gas turbine model is used to represent the prime mover as shown in the figure 2. [6]

2.2.5. Load model

The loads in the industrial plant are mainly induction motors. The 6.6kV induction motors connected to 6.9kV bus are individually represented by a circuit model as shown in the figure 4. The 0.38kV motors at each bus are lumped at its bus and expressed by the same model. [8],[9]

The equation of motion is as follows.

$$\frac{dS}{dt} = \frac{1}{2H_m}(T_m - T_e) \tag{16}$$

$$T_m = a + b\,\omega_m + c\,\omega_m^2 \tag{17}$$

$$T_e = 3\frac{p}{2}\frac{R_r}{S\omega_s}I_r^2 \tag{18}$$

2.3 Dynamic simulation on a sample power system

2.3.1. Case study

The rating of generator employed for this analysis is 12.5MW, 6.9kV, 50Hz. There are a number of 6.6kV induction motors at the load bus, the ratings of which are in the range of 300kW to 7,000kW. The 0.38kV induction motors are connected to their relevant 0.4kV bus. In order to calculate the frequency decline according to the amount of over-load at the generator, the scenarios of 110%, 120%, 130%, 140%, 150%, 160% of the generator's maximum capacity are simulated.

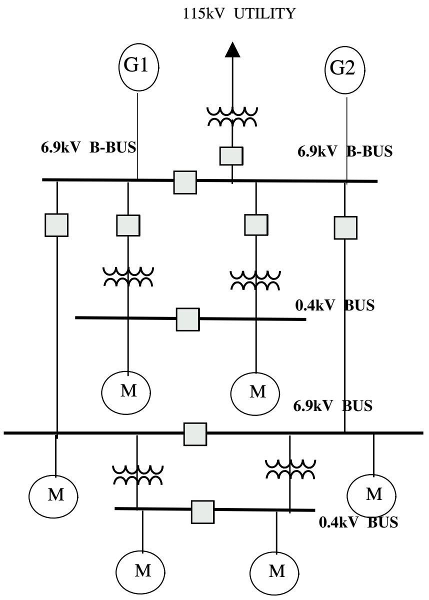

그림 1 간략화한 단선도
Fig. 1 Simplified one line diagram

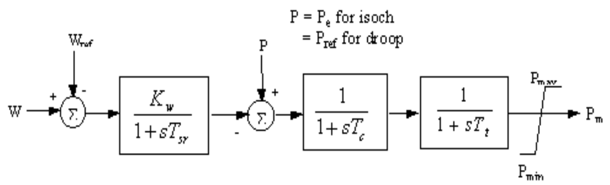

그림 2 가스터빈 모델
Fig. 2 Gas turbine model

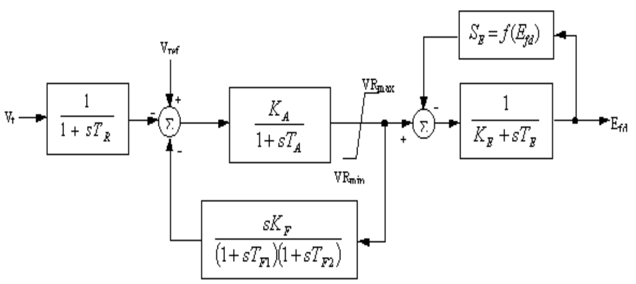

그림 3 IEEE 여자기 타입2, 회전정류기 시스템
Fig. 3 IEEE Exciter Type 2 Rotating rectifier system

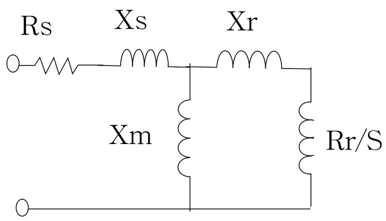

그림 4 유도전동기 용 회로 모델
Fig. 4 Circuit model for induction motor

Two cases are simulated. Those are :

Case 1 is that generators are over-loaded due to outage of utility tie-line without a fault at the power system.

Case 2 is that generators are over-loaded due to outage of utility tie-line after a fault at the power system.

The period of fault is taken as 0.1 seconds which is the shortest possible time achievable from the instantaneous over current relay.

2.3.2. Case study result

The case 1 results are shown in the figures 5 through 10. The amount of frequency decline gradually increases in proportion to over-loading at the generator. The frequency settles at a certain frequency. This kind of frequency decline pattern will enable the frequency load shedding with a frequency threshold (for example 48Hz or 47Hz) and proper timer setting. Motor terminal voltages (Vm) remain above 80% of the motor rated voltage. The slips of motors also gradually increase in proportion to the over-loading and settle at their relevant slip. (Note: The minimum allowable voltage for starting is 80% of rating typical for NEMA design B induction motor.)

The case 2 results are shown in the figures 11 to 16.

In the over-loading cases of 110%, 120%, and 130%, the amount of frequency decline gradually increases in proportion to over-loading at the generator. Motor terminal voltages (Vm) return above 80% of the motor rated voltage in about 1 second after the fault being cleared. The slips of motors also gradually increase in proportion to the over-loading and settle at a certain slip.

In the over-loading cases of 140% and 150%, the motor voltages (Vm) restore to 80% taking about 1.5 second and 3 seconds after the fault being cleared, and then drop below 80%. This is because induction motors re-accelerate secondly due to the voltage drop by the first re-acceleration after the fault clearance.(See figure 15) The motor re-acceleration draws a large amount of reactive power and causes the voltage collapse to begin. The frequency initially decreases below 47Hz, but returns to the rated frequency of 50Hz without continuing to decrease. This frequency pattern makes failure in the pick-up of frequency relay with a frequency threshold and time setting of a few seconds. An additional load shedding scheme initiated by a voltage relay is required. The slips of motors also gradually increase in proportion to the over-loading.

In the over-loading cases of 160%, the motor voltages (Vm) do not restore to 80% and remain about 60% because of re-acceleration of induction motors. The frequency does not decrease and remains above about the rated frequency of 50Hz. This frequency pattern makes failure in the frequency load shedding. An additional load shedding scheme initiated by a voltage relay shall be applied. The slips of motors largely increase. Motors are moving towards stop. The generator current increases largely with terminal voltage below 70%, which will activate the generator tripping by a voltage restraint over current relay(51V) at the generator terminal, and resulting in black-out finally.

2.3.3 Knee point of frequency decline caused by voltage collapse

As indicated in the above simulation on the case of over-load after fault, the generator frequency does not decline any more in proportion to the amount of over-load from the case of 140% over-load, which is the knee point where the voltage instability begins to occur due to reactive power required by re-acceleration of induction motors.

At the over-load of 140% load (knee point) and 150% load, 160% load passing the knee point, the voltage does not recover 80% or remain below 80% of the rating. The active power to be consumed in the induction motor is also reduced, the generator electrical power(Peg) becomes close to or smaller than the initial generation (initial Peg = initial Pmg) (see figure 11). Therefore the frequency does not decline any more and become close to the 50Hz or above. This makes failure in the pick-up of frequency relay.

표 1 과부하 별 전압회복 상태와 주파수 강하 변곡점 (사고 난 경우)

Table 1 voltage recovery per amount of over-load and knee point of frequency decline (in case of fault)

over-load (Peg/Pmg)	time required to return 80% voltage	Is frequency decline in proportional to the amount of over-load
110%	< 1 second	yes
120%	< 1 second	yes
130%	< 1 second	yes
140% (knee point)	initially return, but drop below 80%	no
150%	initially return, but drop below 80%	no
160%	not come back to 80%	no

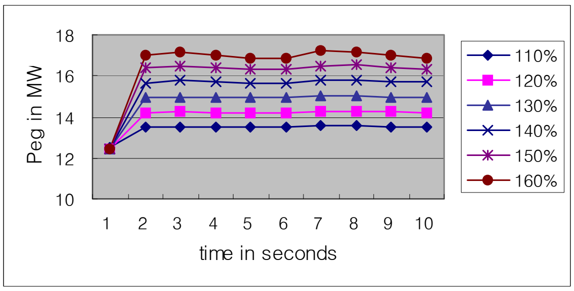

그림 5 무사고 상태 과부하조건의 발전기 전기 출력 (Peg)

Fig. 5 Generator electrical power (Peg) for over load without fault

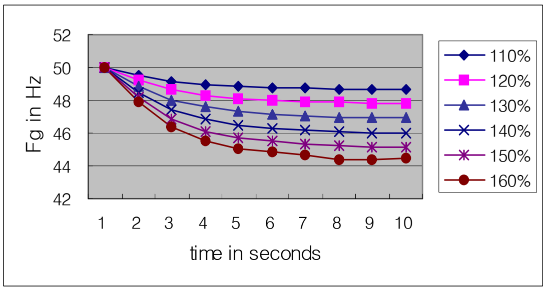

그림 6 무사고 상태 과부하 조건의 발전기 주파수 (Fg)

Fig. 6 Generator frequency (Fg) for over load without fault

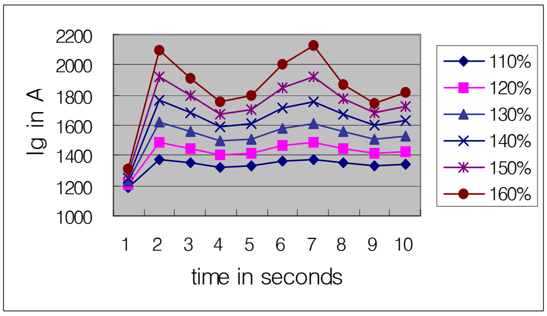

그림 7 무사고 상태 과부하 조건의 발전기 전류(Ig)

Fig. 7 Generator current (Ig) for over load without fault

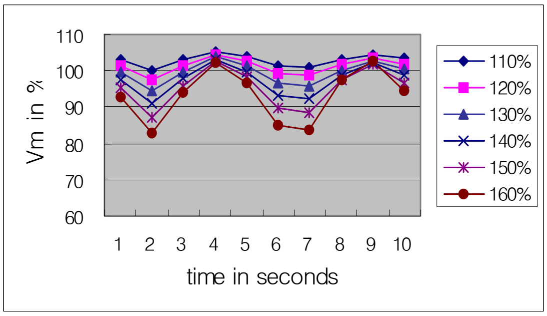

그림 8 무사고 상태 과부하 조건의 전동기 전압(Vm)

Fig. 8 Motor terminal voltage (Vm) for over load without fault

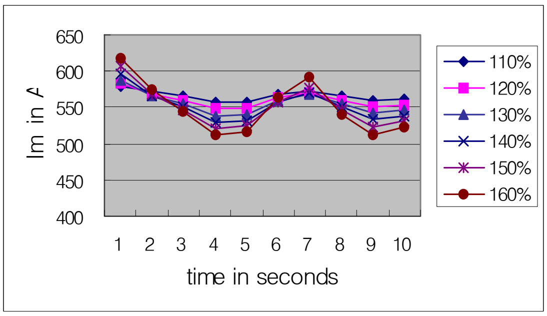

그림 9 무사고 상태 과부하 조건의 전동기 전류(Im)

Fig. 9 Motor current (Im) for over load without fault

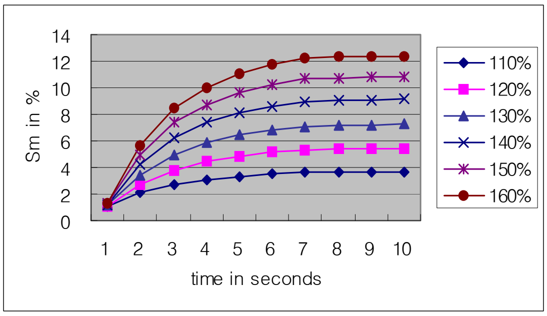

그림 10 무사고 상태 과부하 조건의 전동기 슬립(Sm)

Fig. 10 Motor slip (Sm) for over load without fault

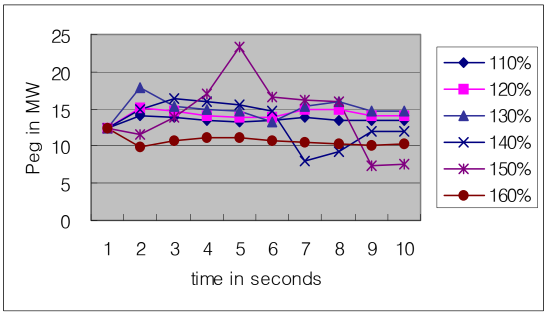

그림 11 사고 후 과부하 조건의 발전기 전기 출력(Peg)

Fig. 11 Generator electrical power (Peg) for over load after fault

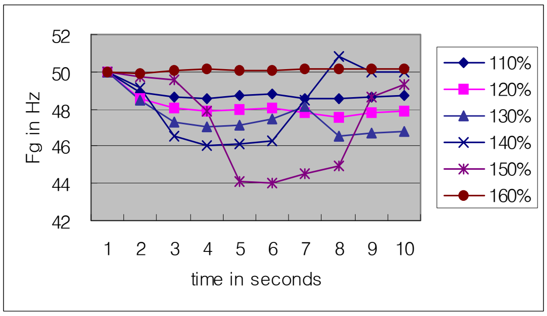

그림 12 사고 후 과부하 조건의 발전기 주파수 (Fg)

Fig. 12 Generator frequency (Fg) for over load after fault

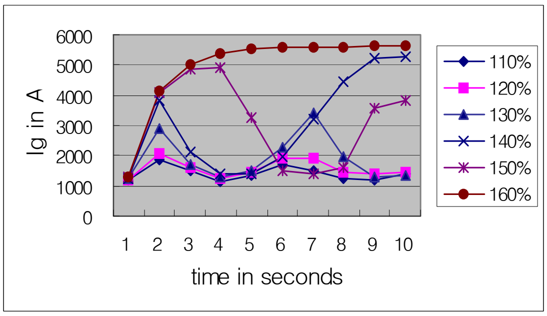

그림 13 사고 후 과부하 조건의 발전기 전류(Ig)

Fig. 13 Generator current (Ig) for over load after fault

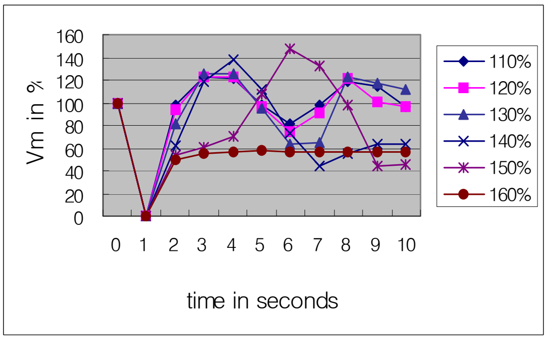

그림 14 사고 후 과부하 조건의 전동기 전압(Vm)

Fig. 14 Motor terminal voltage (Vm) for over load after fault

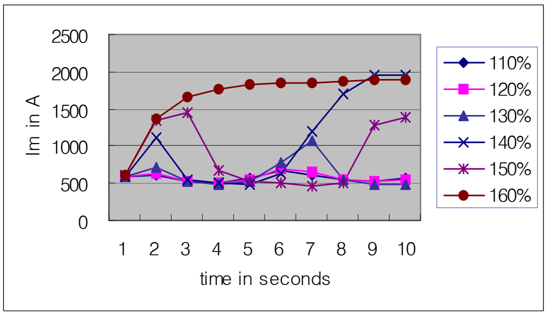

그림 15 사고 후 과부하 조건의 전동기 전류(Im)

Fig. 15 Motor current (Im) for over load after fault

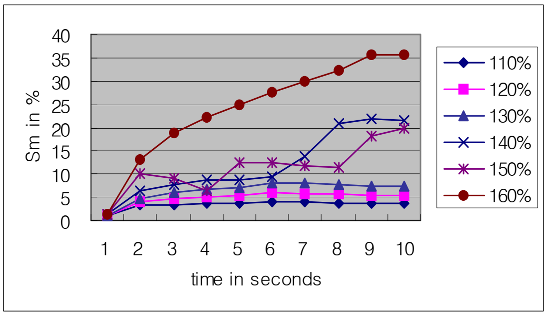

그림 16 사고 후 과부하 조건의 전동기 슬립(Sm)

Fig. 16 Motor slip (Sm) for over load after fault

4. CONCLUSION

A design of load shedding system relying on frequency relays has been so far implemented to resolve the power deficiency problem in the industrial power systems. This was a design practice considering angular stability of the power system. When a tie line is lost by system faults, the transient voltage dip during the period of fault causes re-acceleration of induction motors and voltage instability in the power systems. This voltage instability prevents frequency decline in case of excessive over-loading at generators and results in failure of frequency load shedding.

This paper has presented, taking an example of real gas separation plant, dynamic analysis on frequency decline caused by the amount of over-load at the generator and the knee point causing voltage instability due to reactive power required by re-acceleration of induction motors, and resulting in phenomena of failure in frequency load shedding. A design of load shedding system employing under-voltage relays has been proposed to the industrial power system containing large induction motors in addition to the conventional frequency load shedding.

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부 록 및 약 어

Xd′ = Direct-axis transient synchronous reactance
Xq′ = Quadrature-axis transient synchronous reactance
Xd = Direct-axis synchronous reactance
Xq = Quadrature-axis synchronous reactance
Ra = Armature resistance
T′do = Direct-axis transient open circuit time constant
T′qo = Quadrature-axis transient open circuit time constant
H = Inertia constant of the shaft (MW.sec/MVA)
D = Load damping factor
Pm = Mechanical power in p.u.
Pe = Electrical power in p.u.
ω = Rotation speed in p.u.
δ = Rotor angle in p.u.
Efd = Field voltage acting along the quadrature-axis.
f (Eq) = Function to account machine saturation effect
E′q = Quad.-axis comp. of the voltage behind the equiv. react.
E′d = Direct-axis comp. of the voltage behind the equiv. react.
Eq = Quad.-axis comp. of the voltage behind the equiv. react.
Ed = Direct-axis comp. of the voltage behind the equiv. react.
Ei = Voltage proportional to field current
It = Machine terminal current
Id = Direct-axis component of machine terminal current
Iq = Quadrature-axis component of machine terminal current

<u>Gas turbine model</u>

Mode	Droop or Isoch.
Droop	Steady-state speed droop in %=1/Kw
Pmax	Maximum shaft power in MW
Pmin	Minimum shaft power in MW
Tc	Governor reset time constant in sec.
Tsr	Speed relay time constant in sec.
Tt	Turbine relay time constant in sec.

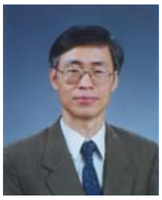
<u>IEEE type 2 rotating rectifier system</u>

VRmax	Max. value of the regulator output voltage, p.u.
VRmin	Min. value of the regulator output voltage, p.u.
SEmax	The value of excitation function at Efdmax
SE.75	The value of excitation function at 0.75 Efdmax
Efdmax	Maximum exciter output voltage, p.u.
K_A	Regulator gain in p.u.
K_E	Exciter constant for self-excited field in p.u.
K_F	Regulator stabilizing circuit gain in p.u.
T_A	Regulator amplifier time constant in sec.
T_E	Exciter time constant in sec.
T_{F1}	Regulator stabilizing circuit 1st t.c. in sec..
T_{F2}	Regulator stabilizing circuit 2nd t.c. in sec.
T_R	Regulator input filter t.c. in sec.

<u>Circuit model of induction motor</u>

Rs	Stator resistance
Xs	Stator reactance
Xm	Magnetizing reactance
Rr	Rotor resistance
Xr	Rotor reactance
S	Slip of motor
Tm	Mechanical torque in p.u.
Te	Electrical :electrical torque in p.u.
Hm	Inertia constant of rotor in MW.s/MVA
ω_m	Motor speed in p.u.
ω_s	Synchronous speed in p.u.
p	Number of pole

저 자 소 개



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