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Modeling and Strategic Startup Scheme for Large-Scaled Induction Motors

Jung Won-Wook[1*], Shin Dong-yeol[1], Lee Hak-ju[1] and Yoon Gi-gab[1]

대용량 유도기 기동 특성 모델링 및 전략적 기동 방법에 관한 연구

정원욱[1*], 신동열[1], 이학주[1], 윤기갑[1]

Abstract This paper is intended to solve the technical problem that fails in large-capacity induction motor starting due to serious voltage drop during starting period. One induction motor that is established already can reach in steady-state using reactor starting method but the voltage magnitude of PCC (point of common coupling) has dropped down a little. When the same capacity induction motor is installed additionally in the PCC, where the existing induction motor is operating, voltage drop becomes more serious by starting of additional induction motor. As a result, the additional induction motor fails in starting. Therefore, voltage compensation method is proposed so that all of two induction motors can be started completely. First, modeling technique is described in order to implement starting characteristics of large induction motor. And then, this paper proposes strategic starting scheme by proper voltage compensation that use no-load transformer tap control (NLTC) and step voltage regulator (SVR) for starting of two large induction motors successfully and improving the feeding network voltage profile during the starting period. The induction motor discussed in this paper is the pumped induction motor of 2500kVA capacity that is operating by KOWACO (Korea Water Resources Corporation). Modeling and simulation is conducted using PSCAD/EMTDC software.

Key words : Induction motor, Inrush current, Starter, Reactor starting, Starting torque, Torque-Speed curve, NLTC (No-Load transformer Tap Control), SVR (Step Voltage Regulator)

요 약 본 논문은 대용량 유도전동기가 기동할 때 발생하는 큰 돌입전류로 인해 PCC(Point of Common Coupling)에 심한 전압 강하가 발생하게 되어 기동에 실패하는 문제를 해결하기 위해 대상 유도전동기의 기동 특성과 배전계통을 모델링하고 시뮬레이션을 수행함으로써 유도기 기동시에 전압저하 현상을 해석하였다. 문제가 되는 유도전동기는 2500KVA용량의 펌프용 농형 유도전동기로 리액터 기동법을 채용하고 있다. 2500KVA 유도전동기 한대의 기동에는 문제가 없으나 기동 완료 후 PCC 전압이 다소 떨어진다. 하지만 추가로 동일 용량의 유도전동기가 기동하게 되면 PCC의 심한 전압강하로 기동에 실패하게 되는 문제가 발생하였다. 이러한 문제 해결을 위해 본 논문에서는 실제 기기의 기동시 토크-속도 곡선을 이용한 유도전동기의 기동 특성을 정확히 모델링하고 시뮬레이션을 수행하여 두 대의 대용량 유도전동기가 순차적으로 기동에 성공할 수 있는 적절한 전압보상 방안을 제안하였다. 본 논문에서 논의되는 대용량 유도전동기는 한국수자원공사의 취수장에서 운전되고 있으며 대상 유도전동기 및 배전계통은 PSCAD/EMTDC 소프트웨어를 사용하여 모델링 및 시뮬레이션을 수행하였다.

1. Introduction

Full voltage starting of a large induction motor could cause serious problems on a limited capacity power system. A typical induction motor might have six or seven times rated inrush current at approximately 0.15-0.25 power factor. Not only does this high inrush current result in a large voltage drop on a distribution line, but the high reactive current at low power factor does also not produce torque efficiently. Some of the usual methods including

[1]The Korea Electric Power Research Institute(KEPRI)
*Corresponding author: Won-Wook Jung(wwjung@kepri.re.kr)

auto-transformer, reactor, and unit-transformer starters can reduce the voltage drop. Unfortunately, all of these methods result in reduced starting torque, and a motor startup under heavy load condition may not be able to accelerate. [1-3]

The induction motor discussed in this paper is the pumped induction motor of 2500kVA capacity that is operating in the KOWACO (Korea Water Resources Corporation). One induction motor that is established already can reach in steady-state using the 80% tap of reactor starter but the voltage magnitude of PCC has dropped down a little. When the same capacity induction motor is installed additionally in this distribution system, voltage drop of distribution line becomes more serious by starting of additional induction motor. As a result, additional second induction motor fails in starting.

First of all, modeling technique is proposed and can implement starting characteristics of large induction motor with pumped load. And then, voltage compensation method that use no-load transformer tap control (NLTC) and Step voltage regulator (SVR) is proposed for starting of two large induction motor loads successfully and improving the feeding network voltage profile during the starting period. When the induction motor is startup with the 80% tap of reactor starter, the PCC voltage is dropped down about 20% from the simulation results and measurement data. And in this condition, when the other motor is startup in sequence, the PCC voltage is dropped down about 30% during starting period. Using the proposed voltage compensation method, the PCC voltage is maintained enough to accelerate the rotor speed of the motors during starting period with 15% voltage compensation. Therefore, all of the two induction motors can be started completely. [4]

1.1 Reduced voltage starting methods

One of the popular starting methods which are used to limit inrush current is the reduced voltage starting method. This method can be achieved in use of auto-transformer, wye-delta connection, primary resistor/reactor. The concerned induction motors are started using a reactor starter with 80% tap in this industry, KOWACO. Therefore, the study of induction motor startup is conducted using reactor starter method. Reactor starting is implemented by placing an inductance in series with the motor leads in order to reduce the inrush current. When the rotor rotating velocity is nearly up to rated speed, the reactor is switched out of the circuit. With this reduced voltage starting, the current drawn by the motor decreases linearly with a decreasing voltage. And also, the electromagnetic torque is reduced by the square of the percent voltage ratio, i.e. 80% reduced voltage with the 80% tap of reactor results in 64% reduced torque, $(0.8pu)^2 =0.64pu$, of nominal torque at full voltage condition. The electromagnetic torque of a machine is derived by following equation at any speed and reduced voltage condition. [5]

$$T_e = kSV^2 \tag{1}$$

T_e: Electromagnetic torque

S: Slip speed

V: Terminal voltage of induction machine

where k is constant which is determined by design specification.

1.2 Swing Equation

In this section, let us consider swing equation for the analysis of the rotating machine dynamics. It can be explained whether an induction machine can reach the steady state speed or not by following swing equation.

$$J\frac{dw}{dt} = T_e - T_m \tag{2}$$

where J is the inertia constant in kWs/kVA, T_m is the mechanical load torque, T_e is the electromagnetic torque in per unit notation, and w is rotor speed. The differential equation (dw/dt) describing the rate of the change of rotor speed (w) means rotor acceleration speed. If T_e is larger than T_m, the differential equation (dw/dt) has a positive value so the rotor speed is accelerated. On the other hand, if T_e is smaller than T_m or same values, the rotor speed can not be accelerated or be decelerated. In this condition, rotor speed stay in starting transient condition and the machine fails In reach the steady state. Therefore, the condition which the rotating machine can be started successfully is that T_e can overcome T_m continually since rotor speed reaches the steady state. T_e is related with terminal voltage of the motor like as equation (1). Therefore, terminal voltage needs to be maintained enough to accelerate rotor speed for successful startup of the motors.

2. Modeling of induction motor starting

2.1 2500kVA Squirrel cage induction motor

There are four fully developed machine models available in EMTDC software. Induction motor modeling is conducted using a squirrel cage induction model (SQC100) as Fig. 1. This model can be operated in either speed control or torque control mode.

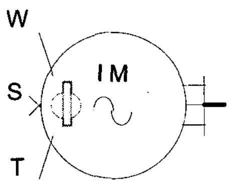


Fig 1. Squirrel cage induction model (SQC100)

In speed control mode, the machine rotates at the speed specified at the input *w*. In torque control mode, the speed is calculated based on the machine inertia, damping, the input torque and the output torque at the input *T*. In Fig. 1, input signal S is used to select induction motor operation mode. The machine is operated in speed control mode with the S input set to 1 and then torque control mode is implemented with the S input set to 0.

There are three data entry methods available in this component such as Explicit, Typical and EMTP Type40. This paper adapts the EMTP Type 40 data entry to the induction machine data. The parameters are entered based on the steady state Torque - Slip curve. The data entry includes power factor, efficiency at rated load, the slip at full load, starting current at full volts, starting full load torque, maximum full load torque, the number of stator poles, inertia constant and mechanical damping to compensate for friction and windage loss. These parameters are acquired form induction machine manufacturer. This acquired data is inserted to the SQC100 model. The inserted data for internal parameters of induction machine is indicated in Table 1.

Table 1. Internal Parameters of SQC100 Model

[sqc100] Squirrel Cage Induction Model

EMTP Type 40 format

Design Ratio	1.0 [p.u.]
Power factor at rated load	0.86 [p.u.]
Efficiency at rated load	0.962 [p.u.]
Slip at full load	0.008 [p.u.]
Starting current at full volts	5.5 [p.u.]
Starting Torque at full volt / Full load torque	0.896 [p.u.]
Maximum Torque / Full load torque	1.955 [p.u.]
Number of poles	8
Polar moment of inertia (J)	150
Units of the inertia	kgm**2
Mechanical Damping	0.008 [p.u.]

2.2 Modeling of induction motor starting characteristics

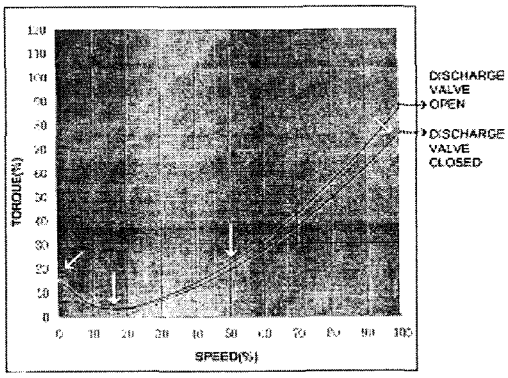


Fig 2. Real starting torque-speed curve

The real starting torque-speed curve of 2500kVA induction motor with large pumped load which is acquired from manufacturer is shown in Fig. 2. The loading of induction motor varies with respect to speedup during starting period as shown in Fig. 2. This paper proposes the modeling scheme of induction machine starting characteristics using real torque-speed curve. This torque-speed curve is implemented by third order mathematical function with respect to rotor speed (w) as equation (3). For deriving the torque-speed function, first, 4 points over the real starting torque-speed curve, (0, 0.15), (0.15, 0.04), (1, 0.75), (0.5, 0.2), are selected and then four simultaneous equations are derived as following equation (4), (5), (6), (7). These four equations pass the selected 4 point respectively. By calculation these four simultaneous equations, the coefficients of equation (3) are derived. Finally, torque-speed function is derived as equation (8).

$$T_m = Aw^3 + Bw^2 + Cw + D \tag{3}$$

simultaneous equations passing 4 points

$$0.15 = A(0)^3 + B(0)^2 + C(0) + D \tag{4}$$

$$0.04 = A(0.15)^3 + B(0.15)^2 + C(0.15) + D \tag{5}$$

$$0.75 = A(1)^3 + B(1)^2 + C(1) + D \tag{6}$$

$$0.20 = A(0.5)^3 + B(0.5)^2 + C(0.5) + D \tag{7}$$

coefficients are derived as following

$$A = -1.6,\ \ B = 3.4,\ \ C = -1.2,\ \ D = 0.15$$

$$T_m = -1.6w^3 + 3.4w^2 - 1.2w + 0.15 \tag{8}$$

The torque equation with respect to rotor speed is implemented in EMTDC as shown in Fig. 3, and than the calculated torque signal is inserted in T terminal of squirrel cage induction model in Fig. 1. The machine is started in torque control mode with T input signal, speed varying torque, in the initial transients of the machine. In steady-state condition, T input has a constant value. As this proposed modeling method, the induction motor starting characteristics are implemented in EMTDC.

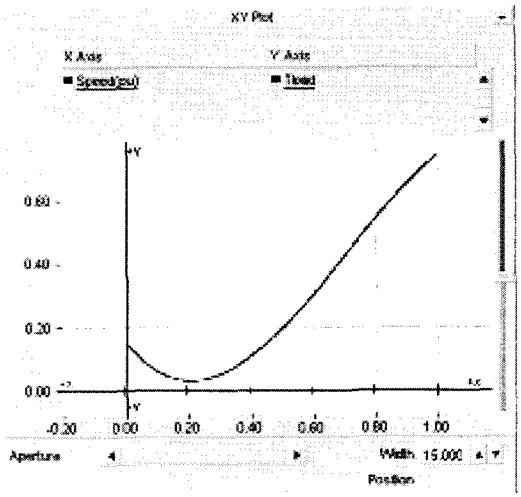
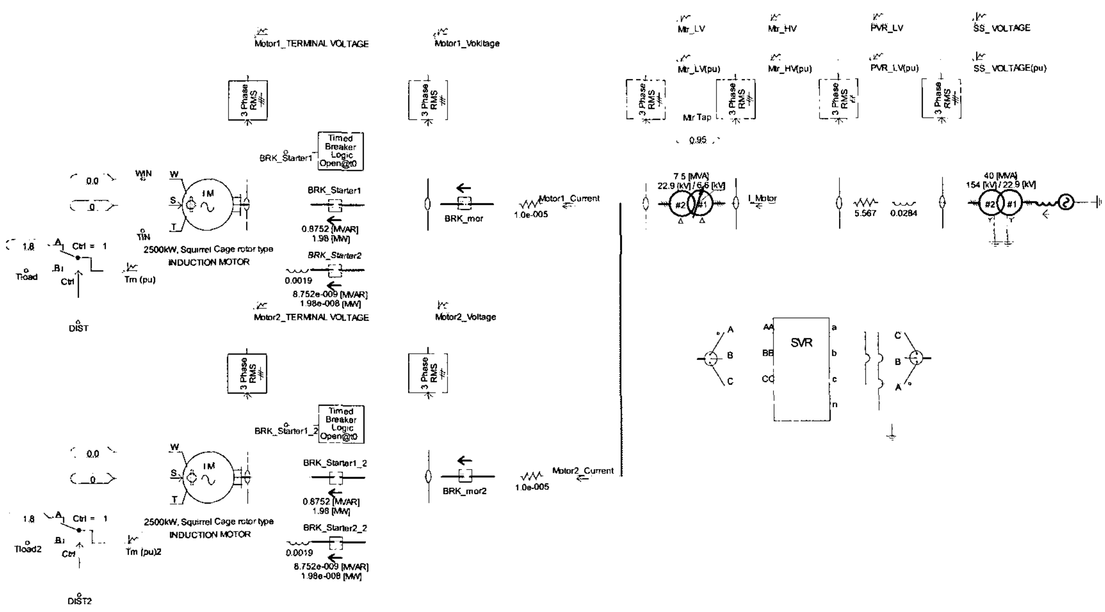


Fig 3. Pumped load Torque-Speed Curve

3. Simulation

In this section, the modeling and simulation is conducted about 2500kVA induction motor that is operating in the KOWACO and is connected local distribution system. First, starting characteristic is simulated by the proposed modeling method at the full voltage condition, and than the simulation results are compared with measurement data to validate the simulation model. Secondly, starting characteristic is analyzed with the 80%, 65% tap of reactor starter respectively. Thirdly, it is studied on starting characteristic with voltage compensation which is conducted with MTr. NLTC and SVR. Finally, this paper proposes voltage compensation strategy for starting of two induction motors in sequence form the simulation study. The developed simulation model using PSCAD/EMTDC is shown in Fig. 4. And the measurement variables are listed in Table 2.



[Fig. 4] Configuration of the simulation model

Table 2. Measurement Variables

VARIABLES	DATA	UNIT
Speed(pu)	Rotor speed	pu
Speed(pu)2	Rotor speed (of #2 induction machine)	pu
Te_electric torque(pu)	Electric Torque	pu
Te_electric torque(pu)2	Electric Torque (of #2 induction machine)	pu
Tm(pu)	Loading mechanical torque	pu
Tm(pu)2	Loading mechanical torque (of #2 induction machine)	pu
I_motor	Current (form S/S to Motor)	kA
Motor2_Current	Current (from MTr. To #2 Motor)	kA
Mtr_HV	MTr. Primary Voltage	kV
Mtr_LV	MTr. Secondary Voltage	kV
TERMINAL VOLTAGE	Terminal Voltage of motor	kV
SVR_LV	Secondary Voltage of SVR	kV

3.1 Full voltage starting

The starting characteristics simulated in the full voltage condition without any starter is shown in Fig. 5. In the simulation results, (a) indicates the rotor speed of the motor which is speed up at 1 second. (b) indicates electromagnetic torque and mechanical torque of the motor. In the full voltage condition, rotor speed is accelerated continuously because the electromagnetic torque (T_e) is larger than the mechanical torque (T_m) since the rotor speed reach to the steady state. (c) indicates phase current feeding motor. The current value has a large current which means inrush current form 1 second to 2.9 second. After motor startup complete, the current value goes to nominal value. (d) indicates the voltages of the MTr. secondary and motor terminal. The voltages drop down severely during starting period.

The measurement data of the induction motor at full voltage is shown in Table 3. As shown in Fig. 5 and Table 3, the simulation results are similar to the measurement data. From the simulation results, the modeling scheme proposed in this paper is validated. When the induction motor starts in the full voltage condition, starting period takes a short time, 1.9 sec, as shown in Fig. 1(a), rotor speed, and the voltage drop down about 30% as Fig. 1(d). However, in the industry, this voltage drop causes the UVR(Under Voltage Relay) of motor protection devise to trip. As a result, the starting in the full voltage condition will be failed.

Table 3. Measurement data of the induction motor.

Item	value
Starting time	1.9 sec
Starting Current	1276.4 A
Full Load Current	232.6A

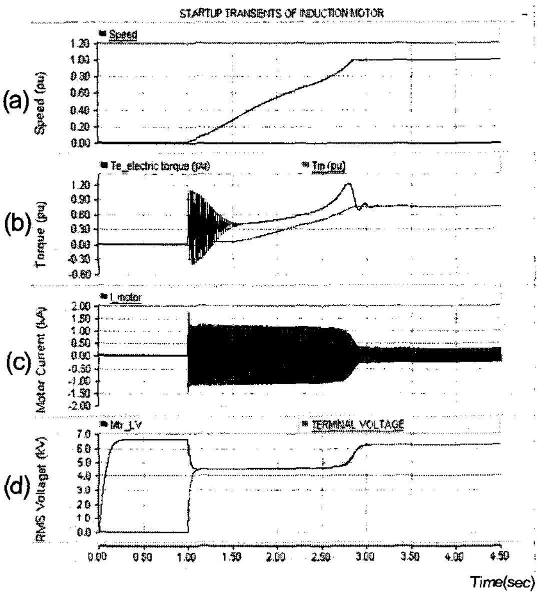


Fig 5. Full voltage starting characteristics : (a) Rotor speed (b) Torque (c) Phase current (d) MTr. secondary voltage and terminal voltage of motor

3.2 Reactor starting

The simulated starting characteristic of the induction motor with 80% tap of reactor is shown in Fig. 6. As shown in Fig. 6, when comparing with the full voltage starting, starting time with 80% tap of reactor takes a long time, 3.9 sec, decreasing a starting current and a voltage drop. Although the starting time becomes long, starting is successfully achieved by decreasing a starting current and a voltage drop. The voltage of MTr. secondary is a little bit higher than the voltage of the full voltage starting as shown in Fig 5. And the terminal voltage is lower than the full voltage condition because the reactor, which is connected between MTr. and motor terminal, reduces the applied voltage at the motor terminal.

In order to reduce the voltage drop during starting period, starting with the 65% tap of reactor is tried as shown in Fig. 7. In this case, the voltage of MTr. secondary is a little higher than the starting condition with the 80% tap of reactor during starting period, but the induction motor can not reach the steady state. In case of using the 65% tap of reactor, the terminal voltage of induction motor is very low as shown in Fig 7. Therefore, low applied voltage can not generate the torque which is acceleration torque for rotor speedup. Due to the low applied voltage, the induction motor has not enough torque and become continuously the starting state. The long time of the starting state cause the induction motor several problems such as burning.

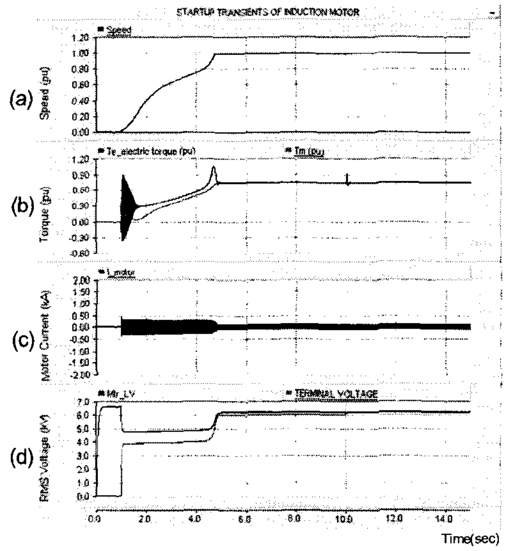


Fig 6. Starting characteristics with 80% tap reactor : (a) Rotor speed (b) Torque (c) Phase current (d) MTr. secondary voltage and terminal voltage of motor

The simulation results of induction motor startup characteristics with respect to applied voltage condition at the motor terminal are listed in Table 4. From the simulation results, reactor starter is useful for improving voltage drop during starting period and reducing inrush current, but when the reactor is installed excessively, 65% tap of reactor, the motor can not complete startup due to reduced acceleration torque. Therefore, it is desirable that the 80% tap of reactor is recommended in this induction motor starting.

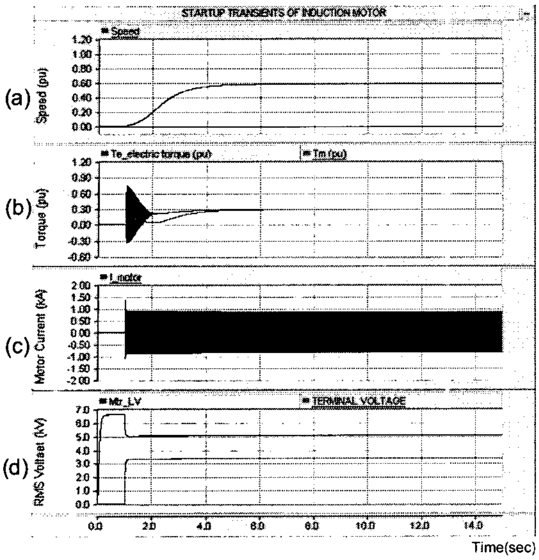


Fig 7. Starting characteristics with 65% tap reactor : (a) Rotor speed (b) Torque (c) Phase current (d) MTr. secondary voltage and terminal voltage of motor

Table 4. Staring characteristics with applied voltage condition

Voltage condition	Starting Time	Voltage of MTr_LV	Voltage of Terminal	Startup complete
Full voltage	1.9sec	4.6kV	4.6kV	Success
80% tap of reactor	3.9sec	4.9kV	3.9kV	Success
65% tap of reactor	-	5.1kV	3.4kV	Fail

3.3 Starting of two induction motor in sequence

The starting of two induction motors in sequence is tried by using the 80% tap of reactor. As shown in Fig. 8, one of the two motors is successfully started within 5 sec. And then, starting of the other motor begins at 8 sec, as shown in Fig. 8. Although starting of the second induction motor begins at 8 sec, the second motor can not achieve the steady state and remains the starting state. In Fig. 8, the starter is removed at 20 sec for protecting the motor. After removing it, the starting seems to succeed at simulation. But, in fact, the PCC voltage drop down enough to trip the UVR and the starting is failed. In this case, second motor with the 80% tap of reactor fails in startup because second induction motor begins startup in low voltage condition arise from the already operating motor in steady-states. This situation through the relation of the electromagnetic torque to the loading mechanical torque is shown in Fig. 8(b), clearly. Because the loading mechanical torque is larger than the electromagnetic torque, the rotor speed can not be accelerated. Therefore, starting of two induction motors in sequence with the 80% tap of reactor should be failed.

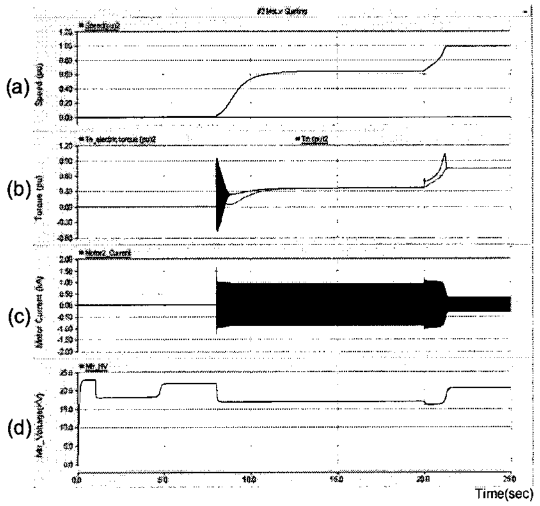


Fig 8. Starting characteristics of second induction motor: (a) Rotor speed (b) Torque (c) Phase current (d) MTr. primary voltage

3.4 Voltage compensation for motor startup

From the above simulation results, for starting the two induction motors in sequence, the proper voltage compensation strategy is demanded. This paper proposes the MTr. NLTC and the SVR as the voltage compensation method.

3.4.1 Voltage compensation method

- The voltage compensation by the NLTC

  By tap change of MTr. Primary side, MTr. secondary could be 5% voltage compensation.

- The voltage compensation by the SVR

  SVR installation at MTr. Primary could improve the PCC voltage about 10%.

The voltage of MTr. Low voltage side with compensations is shown in Fig. 9. The no compensated voltage, 6.6kV, is used as reference in order to compare with the compensated voltage as shown in Fig. 9(a). The compensated voltage by the NLTC becomes 5% increasing, 6.9kV and the compensated voltage by the SVR becomes 10% increasing, 7.3kV, as shown in Fig. 9(b), Fig. 9(c), respectively.

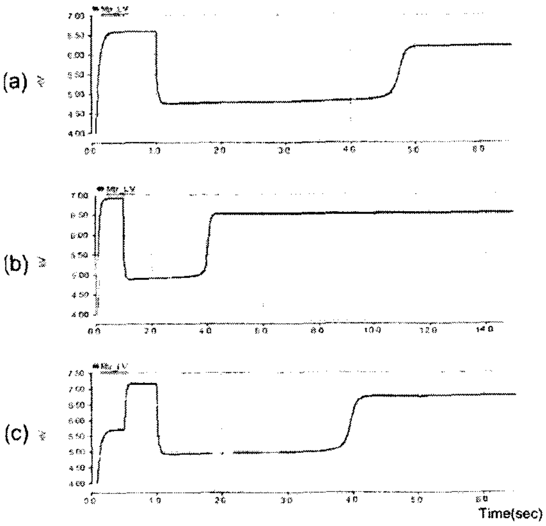


Fig 9. Voltage Profiles with voltage compensation : (a) without compensation (b) with the NLTC (c) with the SVR

3.4.2 Voltage compensation strategy for induction motor startup successfully

In the compensated PCC voltage condition using either 5% compensation with the NLTC or 10% compensation with the SVR installation, startup of two induction motors in sequence is failed from the simulation results.

Therefore, for the successful starting of two induction motors in sequence, this paper proposes the strategic startup scheme with voltage compensation using both the NLTC and the SVR.

If the PCC voltage is compensated using the NLTC and the SVR at the same time in no-load condition, PCC voltage will be overvoltage condition, as shown in Fig. 10. To avoid the overvoltage problem and achieve successful starting of two motors, two compensators should be operated with the following order.

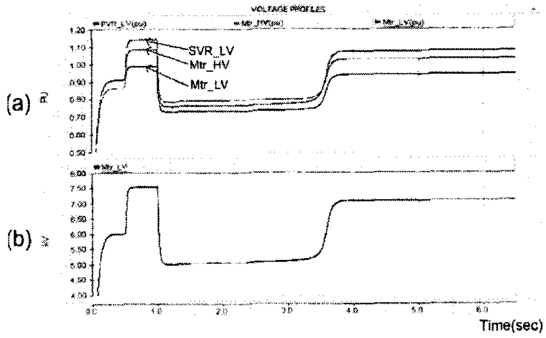


Fig 10. Voltage compensation with NLTC and SVR

- Step 1 : Voltage compensation with the NLTC (5%).
- Step 2 : Starting the first induction motor and achieving the steady state.
- Step 3 : Voltage compensation with the SVR (10%), total compensation is 15%.
- Step 4 : Starting the second induction motor and achieving the steady state.

The Starting of two induction motors is simulated using the proposed method with a simulation sequence listed in Table 5. As shown in Fig. 11, the proposed method succeeds in the starting of two induction motors. Especially, the voltage compensation in sequence uses the NLTC and the SVR as shown in Fig. 11(d).

Table 5. Simulation sequence

Time	Sequence
0.0 sec	MTr. energized (5% voltage compensation with the NLTC)
1.0 sec	#1 Motor startup (with 80% tap of reactor)
4.9 sec	#1 Motor starting complete
5.0 sec	#1 Reactor starter is disconnected
7.0 sec	10% Voltage compensation with the SVR
8.0sec	#2 Motor startup (with 80% tap of reactor)
14.0 sec	#2 Motor starting complete
15.0 sec	#2 Reactor starter is disconnected
20.0 sec	Simulation End

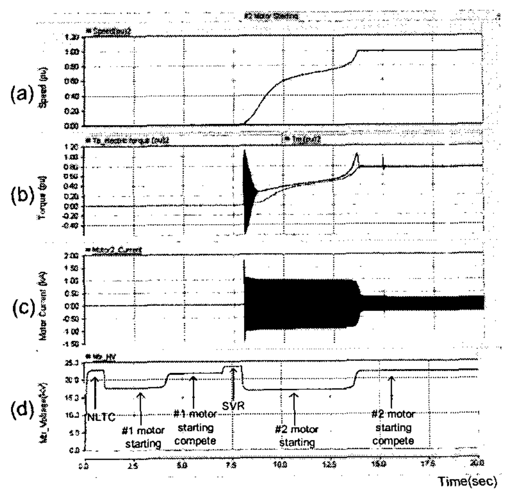


Fig. 11. Starting of second induction motor in sequence with voltage compensation method : (a) Rotor speed (b) Torque (c) Phase current (d) MTr. primary voltage

4. Conclusion

This paper deals with starting problem of induction motor due to serious voltage drop during the starting period. To solve this problem, first of all, the modeling scheme of induction motor starting characteristics is proposed using the real torque-speed curve which is acquired from manufacturer. And then simulation model using the proposed modeling method is validated by comparison the simulation results with measurement data. Secondly, the simulation of induction motor startup characteristics is conducted with respect to applied voltage condition such as full voltage condition, 80% and 65% tap condition of the reactor using the proposed modeling method. From the simulation results, it is desirable that the 80% tap of reactor is recommended in this induction motor starting. But proper voltage compensation method is needed for tow induction motor startup successfully.

Finally, this paper proposes the strategic starting scheme with the voltage compensation using NLTC and SVR in order to complete the startup of two induction motors without overvoltage problem. From the various simulation studies, the following results are obtained

- The reactor starter of the induction motor should be recommended using 80% tap of reactor.
- In order to operate two induction motors in sequence, the voltage compensation is needed by the NLTC and SVR strategically.
- The compensation using both NLTC and SVR at the same time could cause overvoltage problem of PCC voltage. Therefore, the proper operating sequence is demanded for two motors and compensators.
- The proposed strategic startup scheme is verified that starting of two large induction motors is completed successfully and the PCC voltage is improved during the starting period.

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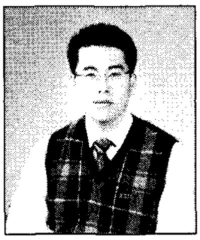
Won-Wook Jung [Regular Member]

Received the B.S. degree in Electrical Engineering from Chungnam National University, Daejeon in 2003 and the M.S. degree from Seoul National University, Seoul in 2005. He worked as a researcher at the Korea Electric Power Research Institute(KEPRI) from 2005 to present. His research field includes power quality, distributed generation and microgrid.

Dong-Yeol Shin [Regular Member]



Received the B.S. degree in Electrical Engineering from Koje college, Koje in 1999. He worked at the branch office of Korea Electric Power Corporation (KEPCO) form 1992 to 2006 and now he worked as a researcher at the Korea Electric Power Research Institute(KEPRI). His research field includes distributed generation, energy conversion and power quality.

Hak- Ju Lee [Regular Member]

Received the M.S. degree in Electrical Engineering in 1991 and the Ph.D degree in 2003 from Chungnam National University, Daejeon. He worked as a senior researcher in the Korea Electric Power Research Institute(KEPRI) from 1996 to present. His research concerns include power electronics, microgrid and low voltage DC power distribution.

Gi-Gab Yoon [Regular Member]

Received his B.S., M.S., and Ph.D. degree in Electrical Engineering from Hanyang University, Seoul, Korea, in 1983, 1988, and 1999. He has over 15 years of research experience in the field of power systems. He is presently a senior researcher in Distribution power system laboratory and advanced distribution system group at KEPRI(Korea Electric Power Research Institute). His research field includes wind power generation system, distributed generation system and control of power system.