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A Novel Hybrid Sequential Start Control System for Large Inductive Loads

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Abstract – The inrush current of a large inductive load can be reduced with a soft starter; however, the large inrush current caused by simultaneous bulk starts (SBSs) cannot be effectively reduced. In order to reduce the high inrush current and voltage sag owing to the SBSs of large capacity inductive loads within a power network, a novel hybrid sequential start control system is proposed, implemented on embedded systems, and evaluated with a testbed in this study. From the experimental and simulation results of the proposed control system, the inrush current could be effectively restricted below the maximum current capacity of a power distributing board. Moreover, with the proposed system, power cost typically dictated by the peak power consumption can be fairly reduced, and the quality of the power system connected to the inductive loads can be efficiently increased.

Keywords: Sequential start control, Inrush current, Voltage sag, Soft start, Flicker

1. Introduction

In recent years, the use of the inductive loads such as air conditioners and refrigerators has been increasing rapidly during the hot summer season, which occasionally causes problems in the electrical power supply system. When a large inductive load starts, it usually consumes an inrush current that is approximately 5 to 10 times higher than its rated current and causes an instantaneous voltage sag in the power distributing board. Therefore, fast detection algorithms for voltage sags have been researched to protect power systems [1-3]. Moreover, this large inrush current and voltage sag may lead to a malfunction of electrical and electronic devices [4]. In addition, a large inrush current may break down the inductive motor itself or reduce the electric power reserve rate of a transformer in a distributing board [5]. In order to minimize the damaging effects of the starting characteristics of large inductive loads, IEC61000-3-3 in the International Electrotechnical Commission (IEC) was established in 1994 as a standard of electromagnetic compatibility (EMC) and has started to limit the voltage fluctuations and flicker of electrical and electronic devices having a rated current less than 16A [6]. Because the instantaneous voltage fluctuations caused by the starting of large inductive loads are becoming more serious, electrical power systems are becoming more unstable. The IEC61000-3-3 international standard was initially applied to European countries using 230V, 50Hz power systems, and it was specified by EN61000-3-3. Because instantaneous voltage changes are increasingly affecting power systems globally, many countries including Korea (K61000-3-3), Japan (C61000-3-3), China (GB17625-2), and Australia/New Zealand (AS/NZS61000-3-3) accepted the national electric safety code (NESC). In Australia/New Zealand, the instantaneous voltage change as well as current are restricted and the short-term flicker severity (P_{st}) and inrush current are limited to less than or equal to 1.0 and 45A, respectively. These limitations of the inrush current and voltage change are applied to single-phase induction motors that are mainly used in air conditioners, refrigerators, vacuum cleaners, and so on.

Initially, to reduce the inrush current and instantaneous voltage changes, a resistive load (resistor or thermistor) was added to the starting coil only when the inductive load starts. When only a cheap resistive load is applied to a small inductive load, the inrush current and voltage sag are somewhat reduced; however, this improvement decreases as the inductive load increases, and the heat caused by the resistive load increases. Moreover, when the inductive load is successively turned on and off in high-temperature environments, its performance will rapidly decrease, or the resistive load itself may breakdown; thus, this resistive load method is not a suitable solution. As an alternative, a pulse-width modulation (PWM) control using power devices such as a silicon-controlled rectifier (SCR) or triode for alternating current (TRIAC) is used to address the problems mentioned above. Recently a soft starter has been used as an effective and low-cost method of reducing the inrush current and voltage sag through the use of thyristor-based voltage control [7-11].

Although the inrush current of a large inductive load can be limited with the slow starter, the starting time of an inductive load is lengthened. Therefore, it is increasingly possible that, with increased duration, many inductive loads may start at the same time thus accumulating large inrush currents and voltage sags in a distributing board.

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This situation is caused mainly by air conditioners along with other inductive loads in the summer because of the frequent on/off control of large single-phase induction motors. In large office buildings, a heating, ventilation, and air-conditioning (HVAC) system is typically used for optimal control, and air-handling units (AHUs) are not frequently turned on/off; therefore, concurrent starts are under control. However, most middle- or small- sized buildings do not have HVAC systems; thus, many dwellers use air conditioners individually. Therefore, because simultaneous bulk starts (SBSs) will cause this serious problem, a sequential control is necessary for starting air conditioners in this environment, and it is also applicable to the other large inductive loads.

In order to address the SBS problem, a simple sequential start control system (SSCS) using a network-based polling scheme was previously proposed [12]. The proposed control system comprises a master and many slaves having unique IDs equipped in each air conditioner based on power-line communication (PLC) and applied time division multiple access (TDMA). In the applied TDMA scheme that is synchronized with a beacon message from a master, a slave having an assigned ID should be able to start only in its own time slot. Additionally, only a slave that sends a start request message to a master and receives the corresponding response from a master can start in its own time slot. If there is no problem in the control network and any of the slaves, the SBSs will not occur. If not, any/some of slaves never start because a slave does not receive a response from a master. The above problem may occur in two cases. The first one is that there may be several slaves having the same ID in a control network. In this case, a time slot is assigned to more than one slave, and request messages sent from these slaves to a master will collide. Therefore, none of slaves can start because of the absence of a response message from the master. The second case is when there is a problem in a control network. A control network does not work properly for any reason, and a message including beacon, request, and response messages between a master and a slave may not be transmitted. Therefore, some slaves may not start in a control network.

In order to overcome the aforementioned problems of the previous control system, a modified SSCS that satisfies the following requirements is proposed. First, a slave must be able to start within a maximum time delay even when two or more slaves have the same ID in a control network while the expected inrush current is restricted to a fixed value. Second, a slave must be able to start even when the control network is broken or malfunctions. Namely, a slave should be able to recognize the fault situation of a SSCS within a fixed time and should try to start by itself.

In this study, we have discussed the possible problems of the previous SSCS and clearly defined the improvement requirements of the proposed system, and proposed a novel hybrid SSCS to address these problems and requirements. The proposed hybrid SSCS has two different frameworks: one for the prevention of SBSs and the other for permission of SBSs. In fact, the peak inrush current is probabilistically restricted below a fixed value. In addition, to reduce the additive processing and control network loads, the number of message types in the control protocol is minimized, and the messages are simplified. Our hybrid SSCS is implemented on embedded systems and its operations are evaluated on a testbed. In addition, the maximum and average delay times of the start, the expected inrush current of the hybrid SSCS, and the average peak inrush current of the immediate start are simulated. From the simulation results, we can see that the hybrid SSCS can effectively control the start of many inductive loads and probabilistically restrict the inrush current. Therefore, our research work will be very helpful to design a control system with large inductive loads having a constraint on the maximum current capacity in a power distributing board.

The rest of this paper is organized as follows. In section 2, the proposed hybrid SSC is described in detail. The implementation issues and simulation results of our hybrid SSCS are explained and presented in section 3. Finally, the conclusions are discussed in section 4.

2. Hybrid Sequential Start Control System

In order to improve the previous SSCS, a hybrid SSCS that satisfies the two above-mentioned requirements is proposed. For a master to effectively control the sequential start of many slaves in a network, the control network structure is designed as shown in Fig. 1. The proposed hybrid SSCS consists of a master and a number of slaves that are connected by PLC with a bus topology.

Depending on the situation of the control network, the hybrid SSCS is divided into two operation modes; the control mode and the immediate start mode. If a slave receives a beacon message from a master normally, it operates in the control mode. Otherwise, a slave operates in

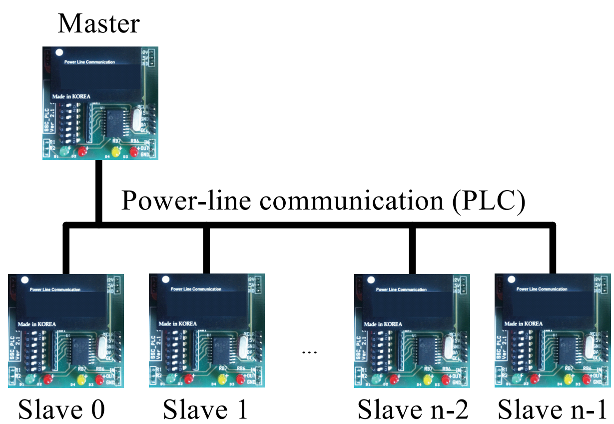


Fig. 1. Network structure of the proposed sequential start control system

the immediate start mode by itself. In fact, the second one is devised to satisfy the second requirement. Therefore, the control mode is mainly described here.

The media access control (MAC) protocol of a wireless communication system is applied to the sequential start control algorithm. The MAC layer provides access control mechanisms that make it possible for nodes to communicate within a multiple access network that incorporates a shared medium. When a collision occurs, all the transferred messages are corrupted. Therefore, the sequential start control has some similarities to MAC, i.e., the power/medium is shared, and both of them try to prevent collisions/SBSs. However, sequential start control is less strict than MAC because the SBSs only rapidly increase the inrush current. Moreover, the power system does not breakdown if the inrush current does not exceed the maximum threshold.

As shown in Fig. 2, the proposed hybrid SSCS is divided into contention-free (CF) and contention-based (CB) control frameworks. In a CF control framework, previously applied TDMA is used depending on the CF beacon message from a master and the assigned ID's of the slaves. In the CF control framework, a slave can start only after it sends a start request message to a master and receives the corresponding response from the master in its time slot assigned by the ID. When a CF control framework is used alone as in the previously applied TDMA [12], both requirements cannot be satisfied. In order to satisfy the first requirement, the CB control framework using a random access method is introduced. Only a slave that fails to start in the CF control (CFC) framework will participate in the CB control (CBC) framework, and it starts unconditionally. After receiving the CB beacon massage, each of the attended slaves in a control network checks whether its start input is activated. If so, the slave will randomly choose a number from the m-integer pool and definitely starts at the chosen time slot without considering the SBSs. Otherwise, a slave has no operation in the CBC framework. In the CBC framework, depending on the size of the integer pool, i.e., the number of time slots in the CB period as shown in Fig. 2, the expected inrush current will be probabilistically restricted, and it will described in detail in section 3.

The CF access scheme for the CF period in the CFC framework and the CB access scheme for the CB period in the CBC framework are shown in Fig. 3. The notation is as follows:

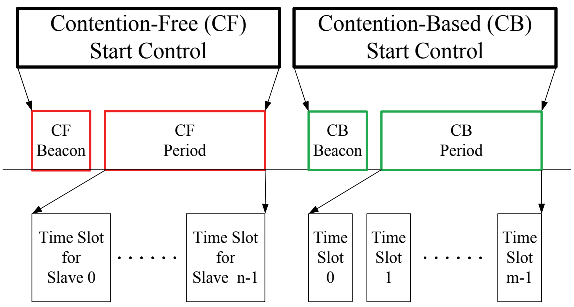


Fig. 2. Framework of the hybrid SSCS

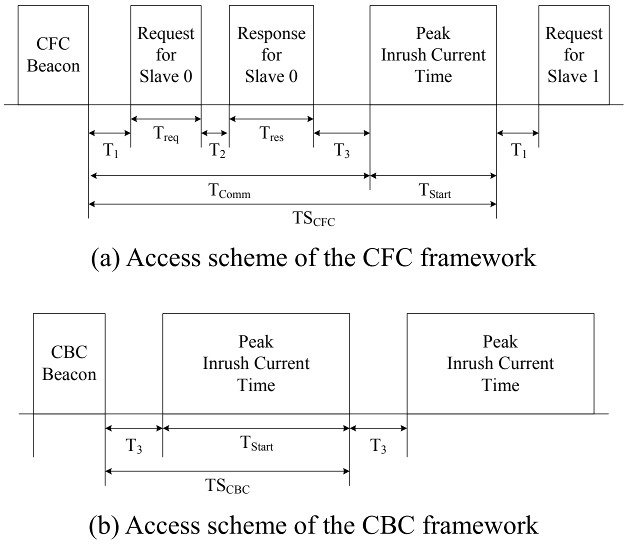


Fig. 3. Access schemes of the CFC and CBC frameworks

- T_{req} : The time for a start request message;
- T_{res} : The time for a start response message;
- T_1, T_2, and T_3: Three different time intervals;
- T_{Comm} : The time for communication;
- T_{start} : The time for starting an inductive load;
- TS_{CFC} : The time of a time slot in the CFC framework;
- TS_{CBC} : The time of a time slot in the CBC framework.

The master synchronizes all the slaves in a control network using the CF and CB beacon messages. First, the access scheme of the CFC framework is described in detail. After a slave receives the CF beacon message, it waits for its time slot assigned by an ID using its internal clock. During the assigned time slot interval, T_1, the slave checks if the start input from a soft-starter board is active. If the start input is not activated, there is no further special operation in this framework. If the start input from the soft-starter board is active, the slave sends a start request message to a master within T_{req}. During interval T_2, the master receives and checks the starting request message of the slave, and if the received request message is valid, it sends a start response message to the slave within T_{res}. Finally, during interval T_3, the slave receiving the corresponding response message sends the active starting output to the soft-starter board to start the inductive load within T_{start}.

Next, the access scheme of the CBC framework is described below. After a slave receives the CB beacon message, it checks if its start input is active during interval T_3 and only a slave whose start input is activated can participate in the CBC framework. That is, the number of slaves in the CBC framework is fixed at this time, and each of the attended slaves has to randomly choose an integer between 0 and m−1 as shown in Fig. 2. Depending on the chosen number, a slave should wait for its time slot and then it definitely starts.

2.1 Master

The primary functions of a master are to synchronize the operations of all the slaves in a control network by sending CF and CB beacon messages and to send the corresponding response to a start request message from a slave as an approval of a start. The functional flowchart of a master is shown in Fig. 4. The number of time slots for the CFC framework, n, and the number of time slots for the CBC framework, m, in the hybrid SSCS are defined. Depending on the adjustable parameters n, TS_{CFC}, m, and TS_{CBC}, the periods of CFC and CBC are determined, and the CF and CB beacon messages can be generated by a master. After a CF beacon message is broadcast, and when a master receives a start request message from a slave during a certain TS_{CFC} in the CFC framework, the master checks whether the slave's ID is the same as the number of the current TS_{CFC}. If so, the master will send the corresponding start response, and if not, no message will be sent. Further, the CB beacon message follows at the end of the CFC framework to indicate the beginning of the CBC framework. Thereafter, a master does not have a special role during the CBC framework except for counting the expiration timer to wrap up a CBC framework. These operations are repeated routinely.

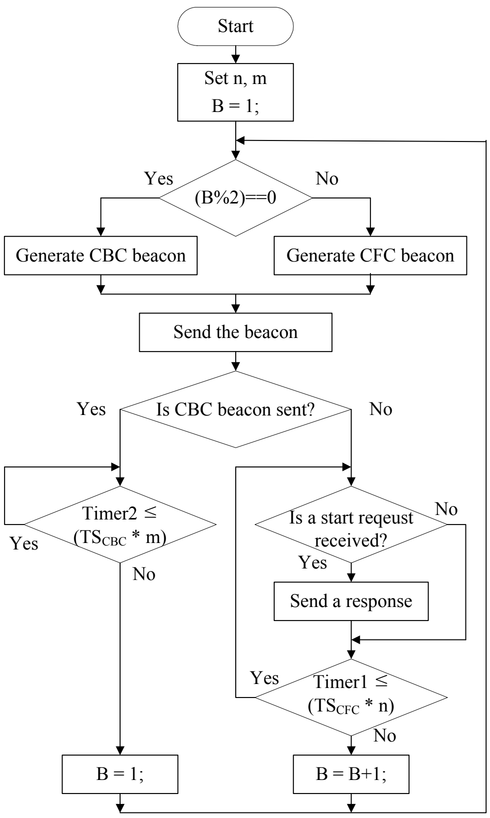


Fig. 4. Functional flowchart of a master

2.2 Slave

A slave device is functionally divided into two parts. One part is for the proposed hybrid SSCS, and the other is for the actual soft-start controller of an inductive load using thyristor-based voltage control. In this paper, the first part is referred to as a slave, and the second part is called a soft starter. A slave has a Start_IN input from the soft starter and a Start_OUT output to the soft starter. A slave checks whether Start_IN is active at its TS_{CFC} for the CFC framework and just after receiving the CB beacon message for the CBC framework. A slave can only attempt to start if Start_IN is active at these two points of time. For a slave to support the second requirement, the immediate start mode is added. The functional flowchart of a slave, including the immediate start mode as well as the control mode (hybrid SSCS operation), is shown in Fig. 5. If the number of the sequential absence of beacon messages is greater than TB_{max} which is an adjustable parameter, a slave has to enter into the immediate start mode until a beacon message is received. There is no sequential start control in this mode:

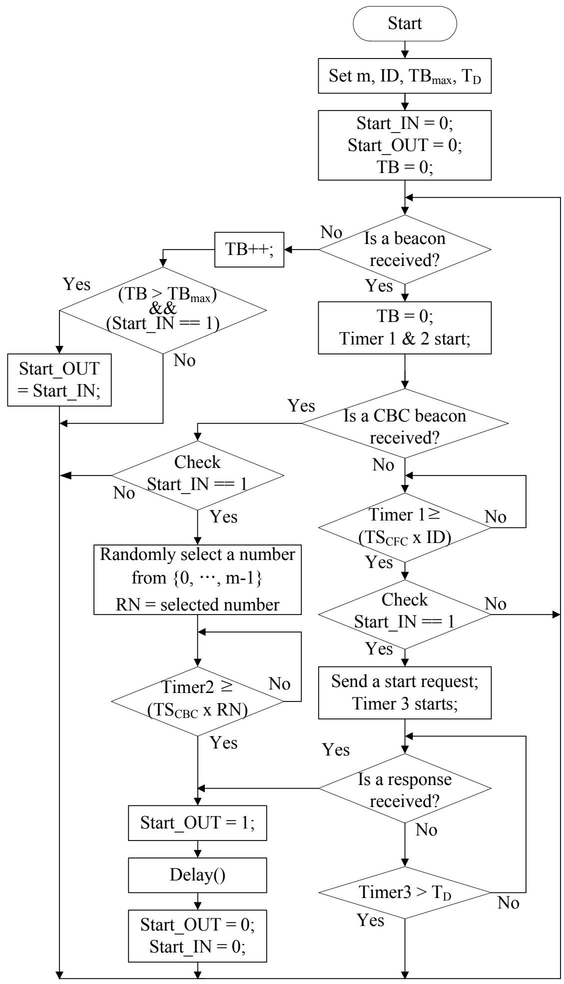


Fig. 5. Functional flowchart of a slave

thus, the Start_IN input is just bypassed to the Start_OUT output.

In the proposed hybrid SSCS, bulk starts are prevented in the CFC framework; thus, no simultaneous bulk starts happens. However, in the CBC framework, the bulk starts are weakly prevented, and the expected inrush current will be probabilistically limited, i.e., there is a likelihood that SBSs occur. Furthermore, the immediate start mode is provided to make the hybrid SSCS robust to control network problems.

3. Implementation and Performance Evaluation

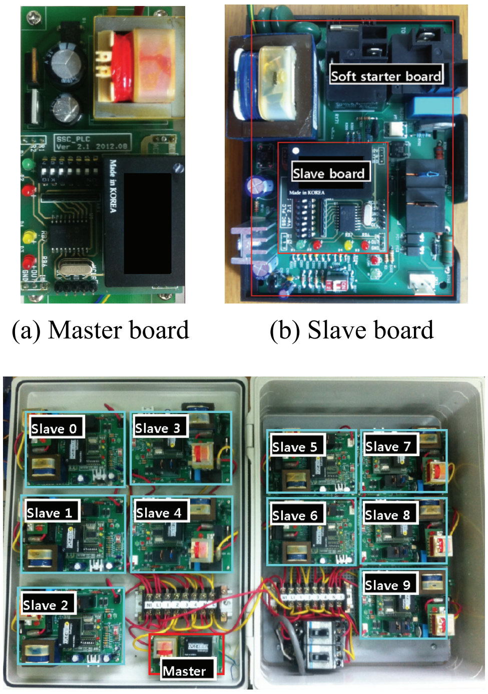
In this section, the implementation environments and the testbed are briefly introduced, and then how to properly design the proposed hybrid SSC is described in detail with the simulation results. Moreover, the performance of the hybrid SSC is compared to the immediate start mode in terms of the average inrush current on the basis of the simulation results.

The proposed hybrid SSCS was implemented on an 8-bit processor based controller considering real product as follows:

- 8-bit Microcontroller
- 20 MHz system clock
- 1024 bytes SRAM
- 256 bytes EEPROM
- 14K bytes program memory
- 4 x 8-bit timers and 1 x 16-bit timer
- 16 GPIOs
- 1 UART
- Bus type 9600 bps power line communication

In order to verify the proper operation of the hybrid SSCS, both a master and a slave are separately implemented on embedded systems, and the three different operations including the CFC and CBC frameworks and immediate start mode are evaluated with the testbed system that comprises a master and 10 slaves as shown in Fig. 6.

In order to properly evaluate the performance of the proposed hybrid SSCS within the given constraints of implementation environments, the variable parameters are set on the basis of our implementation and simulation results, as described in detail below. The variable parameters, T_{req}, T_{res}, T_1, T_2, T_3, and T_{start} depend entirely on the implementation environment. Only T_{start} depends on the soft-starter controller whereas the other parameters depend on the characteristics of the PLC and the sizes of the messages. The length of the beacon, start request, and response message are designed to be 1B (8-bit), 2B (16-bit), and 2B, respectively. T_{req}, T_{res}, T_1, T_2, T_3, and T_{start} are set to be 5ms, 5ms, 3ms, 2ms, 5ms, and 500ms, respectively, to provide enough margin that includes the processing and communication delays. Here, T_{start} is used as the limiting



(a) Master board (b) Slave board

(c) Testbed system

Fig. 6. Embedded systems for the master, slave, and testbed

value of the international standard instead of the measured value (130ms) of the soft-starter controller using TRIAC and PWM. When T_{req}, T_{res}, T_1, T_2, T_3, and T_{start} are fixed, TS_{CFC} and TS_{CBC} are calculated as follows:

$$\begin{aligned} TS_{CFC} &= T_{comm} + T_{start} \\ &= T_1 + T_{req} + T_2 + T_{res} + T_3 + T_{start} \\ TS_{CBC} &= T_3 + T_{start} \end{aligned} \tag{1}$$

In addition, in order to properly determine n and m, it is used that the maximum delay of the start, D_{max}, and the expected inrush current in the CBC framework, $E[I_{inrush}]$, and the time periods are calculated as follows:

$$\begin{aligned} TP_{CFC} &= T_{beacon} + n \times TS_{CFC} \simeq n \times TS_{CFC} \\ TP_{CBC} &= T_{beacon} + m \times TS_{CBC} \simeq m \times TS_{CBC} \end{aligned} \tag{2}$$

Because n is set on the basis of D_{max}, and m and n closely correlate to $E[I_{inrush}]$, m is first set depending on $E[I_{inrush}]$ and is calculated as follows:

$$E[I_{inrush}] = \sum_{i=1}^{m} \binom{m}{i} \times \left(\frac{1}{m}\right)^{i} (i \times I_{inrush}) \tag{3}$$

where, the inrush current, I_{inrush} is used as the limiting value (45A) of the international standard instead of the measured value (37.46A) of our soft-starter board. In the worst case, it is possible that all n slaves participate in the CBC framework because of a malfunction of the communication network, for example, when only the receiver part of a master is broken. In this case, m is set to be n in our implementation.

In order to set the number of TS_{CFC} in the proposed hybrid SSCS, D_{max} should be considered as a constraint of the implementation. Therefore, n should be determined on the basis of D_{max}, and D_{max} is expressed approximately as follows:

$$\begin{aligned} D_{\max} &< TP_{CFC} + 2 \times TP_{CBC} \\ &< n \times TS_{CFC} + 2m \times TS_{CBC} \end{aligned} \quad (4)$$

where, D_{max} occurs when a CB beacon is received just before the Start_IN of a slave is activated; thus, it cannot participate in the CBC framework and will try to start in the next CFC framework. If the slave fails, it participates in the following CBC framework and chooses the last time slot.

In order to simulate the start delay, it is assumed that the inductive loads in a power distributing board are intensively used within two hours, and the active input arrival of Start_IN of a slave among the controlled slaves is an independently and identically distributed Poisson random process with a mean of λ, where λ has a Gaussian random distribution. In our simulation, n is set to be 256, and m is set to be 32 or 64 in (4). In addition, λ is set to be 5, 10, and 15 min with a standard deviation of 0.3. Moreover the adjustable parameters mentioned above are equally used. D_{max} and the simulated average time delays, D_{arg} for three different values of λ are shown in Fig. 7. D_{max} for m = 32 and m = 64 are 168.32s and 197.76s; therefore, it is much greater than the simulation results, as shown in Fig. 7. Also it is shown that the performance of the proposed hybrid SSCS is better than that of the simple SSCS when compared in terms of D_{arg}.

In order to examine the effectiveness of the proposed hybrid SSCS, the average peak inrush currents caused by simultaneous starts in the immediate start operation and the proposed SSCS with n = 256 and m = 32 are simulated. As the number of slaves in the same power distributing board increases, the inrush current is expected to increase rapidly up to a maximum limit if the large inductive motors are not appropriately controlled sequentially. The simulation results

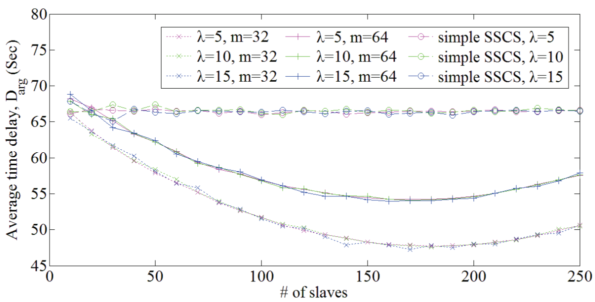


Fig. 7. D_{arg} vs. # of slaves

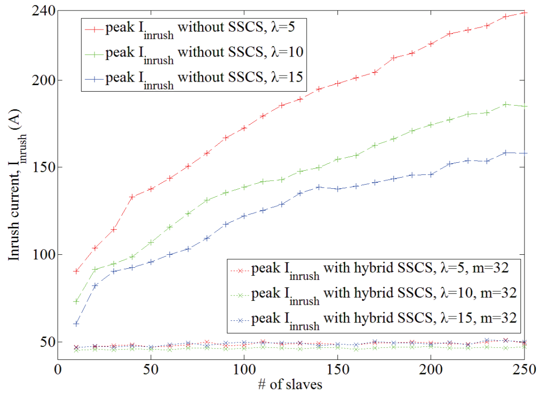


Fig. 8. Averaged peak I_{inrush} vs. # of slaves

for the three different means are shown in Fig. 8. As λ or n increase, the average peak inrush current in the immediate start operation increases drastically, yet the proposed SSCS can properly restrict the peak inrush current.

With the hybrid SSCS, no simultaneous start is expected in the CFC framework, and in the CBC framework, $E[I_{inrush}]$ will be restricted probabilistically by setting an appropriate value for m. Although m is set to be 32 in our implementation, the average peak inrush current is controlled effectively. Thus, the number of slaves is not greatly increased for normal operation. Moreover, m increases for the worst case, $E[I_{inrush}]$ will decrease. Therefore, $E[I_{inrush}]$ will probably be under control. Consequently, the hybrid SSCS is able to sequentially control the start of many inductive loads. Furthermore, the immediate start operation is provided when the control network breaks down.

4. Conclusion

In this study, we proposed a novel hybrid SSCS to address the problem of large inrush currents and voltage sags caused by SBSs and to satisfy the improvement requirements with the minimized processing and communication loads. The hybrid SSCS was implemented, and its operation was evaluated on the testbed. In addition, the hybrid SSCS was verified to operate within the constraints in terms of maximum delay and expected inrush current by using simulation results. Further, the hybrid SSCS was shown to effectively reduce the inrush current when compared with the simulated average peak inrush current of the immediate start mode operation. Therefore, our research work will be helpful in designing a control system with large inductive loads that has a maximum start delay and power constraints.

Acknowledgements

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