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Rotating Machinery Protection
Subcommittee
of the
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Motor Bus Transfer Applications Issues and Considerations

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Report Contents

I. Abstract:

This paper presents the results of an investigation of motor bus transfer (MBT) applications issues and considerations by a Working Group of the IEEE PSRC Rotating Machinery Protection Subcommittee. The specific task was to investigate protection and control issues as well as phenomena impacting the effectiveness of safely transferring buses primarily consisting of motor loads from one power source to another source. Areas addressed are technical literature, manufacturers' information, members experience with plant applications, history, application approaches, computer modeling, field measurements, and industry guidance. This knowledge will help enlighten users to benefit their applications with regard to motor bus transfer protection and control. There are many challenges associated with proper application of motor bus transfer systems. These will be addressed in this paper.

II. Introduction:

The Rotating Machinery Protection Subcommittee of the IEEE Power Systems Relaying Committee has assigned this Working Group the task to investigate protection and control application and issues with regard to motor bus transfer techniques. Since this subject was last addressed in a Working Group Transaction Paper "Motor Bus Transfer" in 1993, technology and transfer techniques have changed and improved. In addition, this report output will be provided to the Working Group revising the C37.96 "IEEE Guide for AC Motor Protection" to update this topic in the Guide. There are a variety of issues with regard to the proper implementation of the motor bus transfer, as well as many concerns that need to be addressed.

III Overview, Scope, and Purpose

A. Overview:

To maintain process continuity, motor buses may require transfer from a old source to a new source. The reasons for this may be fault clearing on the old source, generating unit trips, deliberate transfer from a utility source to onsite source during storm periods or for rate savings (and back to utility power at a later time), and de-energizing the old source for maintenance or construction. A simplified one-line diagram is shown in Figure 1.

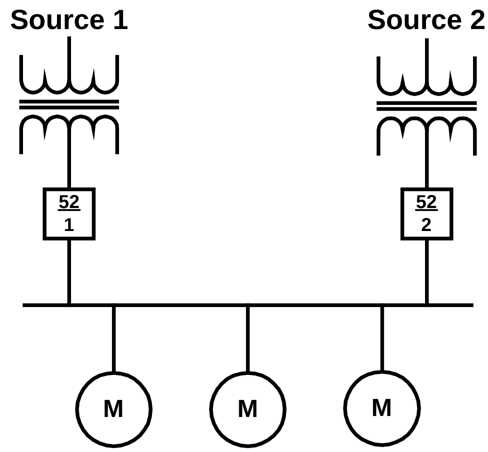


Figure 1 Simplified MBT One-Line Diagram

MBT schemes and systems are employed at power plants and industrial facilities to maintain electrical service continuity in processes served by large motors or aggregates of smaller and large motors. Large motors, of both the synchronous and induction variety, require comprehensive source transfer strategies in order to avoid mechanical damage. The coast down period and resultant voltage and frequency decay requires a supervised source transfer to avoid damage. Mechanical damage may occur in the motor, the coupling to the load or the load itself, and is primarily caused by excessive transient torque. Therefore, the mission of an MBT system is not only to maintain process continuity but also to affect source transfers in such a manner as not to cause any damage to the motors, couplings, and connected loads.

B. Scope:

The scope of this paper includes a basic discussion of motor bus transfer applications including system topologies, classifications, and methods. In depth coverage of dynamic conditions, application issues and concerns are presented. General industry guidance concerning motor bus transfer application is reviewed. In the annex of the paper, case studies, examples of oscillographic data capture during transfers, software simulation modeling examples, and a comprehensive listing of references are provided. It is anticipated that the contents of this paper provides the reader with a good understanding of the significant issues with regard to motor bus transfer application.

C. Purpose:

This Working Group assignment is to provide a recommendation to the Rotating Machinery Protection Subcommittee of the IEEE Power System Relaying Committee regarding proper and safe motor bus transfer control implementation as well as prudent protection for all involved equipment and systems. These recommendations will be incorporated into the next revision of C37.96 – IEEE Guide for AC Motor Protection. This paper presents the results of the Working Group investigation based on industry knowledge, experience, literature, current transfer application implementations, field experience and measurement, and industry experts.

IV. Definitions:

Motor bus. An auxiliary system bus that primarily supplies power to motor loads.

Motor bus transfer. The process of transferring motor bus loads from one power source to another source.

Closed transition transfer (parallel transfer). The process of transferring motor bus load from one source to another source, designed to close the new source breaker before tripping the old source breaker with the result that both sources are briefly paralleled during the transfer process. The closing of the new source breaker is typically supervised to ensure that the voltage phase angle difference between the motor bus voltage and the new source voltage is within a predetermined acceptable limit prior to paralleling the sources.

Open transition transfer. The process of transferring motor bus load from one source to another source, designed to trip the old source breaker before closing the new source breaker so that the two source breakers are open at the same time during the transfer process.

Dead Time. The time period during which the motor bus is disconnected from both sources of power.

Fast transfer - Supervised. The open transition method of transferring motor bus load from one source to another source, designed to trip the old source breaker before closing the new source breaker, whereby the close is supervised to ensure that the voltage phase angle difference between the motor bus voltage and the new source voltage is within a predetermined acceptable limit. Utilizes a high-speed sync-check relay that is accurate and fast enough to detect the change in relative phase angle between the disconnected motor bus and the new source.

Fast transfer - Unsupervised. The open transition method of transferring motor bus load from one source to another source, designed to trip the old source breaker before closing the new source breaker, whereby the close is implemented without a sync-check device or implemented with sync-check relays with performance and response time which may be inadequate.

In-phase transfer. The open transition method of transferring motor bus load from one source to another source, designed to trip the old source breaker before closing the new source breaker, whereby the close command to the new breaker occurs at a phase angle in advance of phase coincidence between the motor bus and the new source to compensate for the new breaker's closing time.

Residual voltage transfer. The open transition method of transferring motor bus load from one source to another source, designed to trip the old source breaker before closing the new source breaker, whereby the voltage magnitude at the motor bus must fall below a predetermined level before the close command is issued to the new breaker. There is no supervision of the synchronous condition between the motor bus and the new source.

Slow transfer. The open transition method of transferring motor bus load from one source to another source, designed to trip the old source breaker before closing the new source breaker, whereby a time interval, usually in excess of 20 cycles, occurs before the load is powered from another source. There is no supervision of the synchronous condition between the motor bus and the new source or of the voltage magnitude of the motor bus.

Sequential Transfer. A "52a," "52b" or "52bb" auxiliary contact of the old source breaker is used to initiate closing of the new source breaker to provide assurance that the bus has been disconnected from the old source prior to closing the new source breaker. Sequential Transfer can be applied with the Fast, In-Phase and Residual methods of transfer to prevent closing the new source breaker should the old source breaker not open.

Simultaneous Transfer. If unsupervised, both breaker actions are initiated at the same time so that the time that the breakers are simultaneously open is minimized. If supervised, the old source breaker is tripped, but closing of the new source is blocked until acceptable predetermined synchronous conditions occur between the motor bus and the new source or until residual motor bus voltage conditions occur. There is no verification that the bus has been disconnected from the old source prior to closing the new source breaker.

Breaker Failure Scheme. During bus transfer, if the new breaker closes and the old breaker fails to open, allowing back feed from the old source, backup breakers to the failed breaker must be tripped. For transfers related to a fault, this reduces equipment damage that could occur due to the excessive fault currents that are available with both sources connected at the same time.

Station Service Source. The power source for the power plant's auxiliary system, typically supplied from the generator bus through the unit auxiliary transformer and auxiliary breaker.

Start-up source. A source of generating plant auxiliary power that is independent of the availability of the main generator.

Normal Power Source (not application specific). The primary power supply to the motor bus load.

Alternate Power Source (not application specific). The backup power supply to the motor bus load.

Planned Bus Transfer. A transfer that is initiated by an operator during a plant start-up or shutdown.

Emergency Bus Transfer. A transfer that is initiated automatically when there is an unplanned unit trip or a sudden loss of the normal or old power source.

Load Shedding. The option of tripping non critical loads during the transfer process.

V. Common Motor Bus Transfer Topologies:

Main-Main Applications

Motor bus transfers are typically done at steam and gas turbine power plants that have significant motor auxiliary loads. The motor bus transfers at these plants were not necessary until the practice of unit connection of generators became the dominant method of connecting generators to the power system. When generators were small (generally below 60 MW) they were typically direct connected. Figures 2a and 2b illustrate both connections.

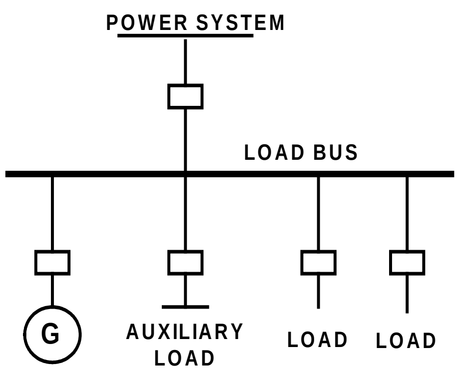


Figure 2a Direct Connected Generator

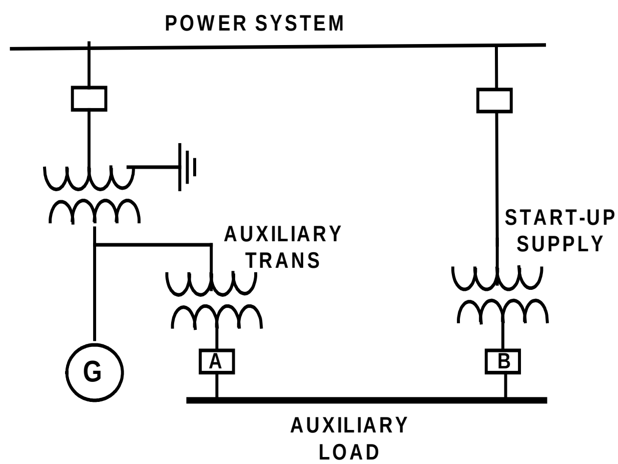


Figure 2b Unit Connected Generator

The unit connected configuration requires a second source of power to the auxiliary load bus, with the auxiliary load served from either the auxiliary transformer or the start-up supply. Many unit connected plants do not have a generator breaker. In this case, the start-up source supplies the auxiliary load when the generator is being started or when it is being shutdown (Breaker B closed and Breaker A open in Figure 2b). When the generator is running the auxiliary load is typically supplied from the auxiliary transformer (Breaker A closed and Breaker B open in Figure 2b). Motor bus transfer is required to safely transfer the loads from one source to another during generator start-up and shutdown. The auxiliary load at power plants consists primarily of motors, which can be damaged if the transfer is improperly made.

Motor bus transfers are done by utilities using different methods based on the situation that requires the transfer.

- Planned Transfers are made when the generator is being started-up or shut down. Typically the plant operator briefly parallels the two sources (Breaker A and B both closed in Figure 2b) and the appropriate breaker is opened to affect the transfer. In many cases these transfers were made without sync-check supervision. Some plants added sync-check supervision to the transfer to prevent closure if the phase angle between the sources was too large.

- Emergency Transfers are necessary when the generator was tripped by protective relays or turbine protection. This required the transfer of auxiliary load from the auxiliary transformer supply to the start-up source (Breaker A opened and Breaker B closed in Figure 2b). These transfers needed to be made automatically. Early schemes used residual voltage transfers where the voltage was allowed to decay to a low level before the breaker to the start-up supply (Breaker B in Figure 2b) was automatically closed. This typically required the tripping of some motor load during the transfer to avoid excessive inrush when re-connecting all the motors on the bus. These motors were then restarted after the transfer to the start-up supply. Thus, not all the motors on the auxiliary system were transferred without interruption. As generators became larger, high speed transfers were employed that used auxiliary breaker contacts to quickly transfer the motors from the auxiliary transformer to the start-up supply. In some schemes, the opening of the auxiliary transformer breaker (Breaker A in Figure 2b) would trigger the closing of the start-up supply breaker (Breaker B Figure 2b). It was commonly assumed the two auxiliary system supply sources were relatively well matched in both phase angle and voltage and that if the transfer were made quickly enough, the motors would support the bus voltage and phase angle to allow the motor to be transferred without damage. In other schemes high speed transfer was supervised with a sync-check relay.

Main-Tie-Main

Motor bus transfer is required at combined cycle power plants and industrial facilities that often use a "main-tie-main" one-line configuration as illustrated in Figure 3.

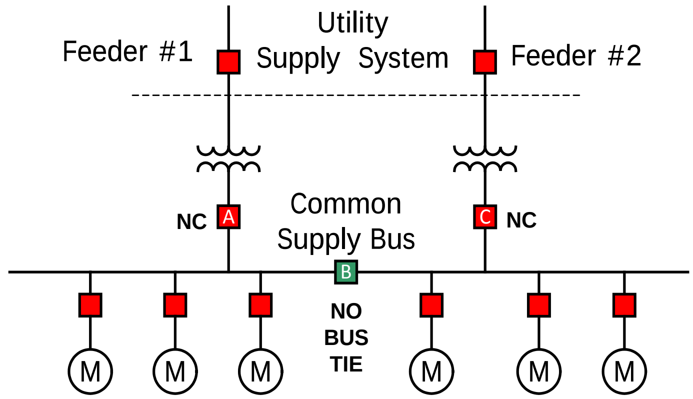


Figure 3 Industrial Facilities - Main-Tie-Main Bus Configuration One-Line

This type of one-line is used at many petrochemical plants in the US as well as in other countries.

- Planned Transfers are necessary to de-energize equipment for maintenance. As in the above described power plant application, planned transfers are made by briefly paralleling the two supplies by closing the bus tie breaker (B in Figure 3) and opening the appropriate incoming supply breaker (A or C in Figure 3) to transfer the motor bus.

- Emergency Transfers are required to transfer load when the utility supply or the supply transformer is tripped due to a short circuit. In the past, residual voltage schemes described above were used to transfer the load to the alternate supply source by tripping the appropriate incoming breaker (A or C in Figure 3) and closing the normally open bus tie (B in Figure 3). Motor contactors on key motors are held closed for a time long enough to allow them to be transferred to the alternate source. As in the power plant application, some motors are tripped to avoid starting inrush, and restarted after the transfer. This practice generally results in some loss of production at the industrial facility.

VI. Motor Bus Transfer Classification and Methods:

Motor bus transfers can be categorized as closed or open transition. The closed transition transfer involves brief paralleling of the sources. The closed transition transfer is also commonly referred to as a hot parallel transfer. Since the new source is connected to the motor bus before the old source is tripped, transfers are completed without source interruption. On the other hand, open transition transfers do not parallel the sources, since the old source is tripped before the new source is connected to the motor bus. Once the motor bus is disconnected, the motors coast down, and reconnection to the new source may require supervision.

In all methods of transfer, if the new source does not meet the criteria for an acceptable source, and if it is possible to stay on the old source, the initiation of the transfer should be blocked. If not possible to stay on the old source, and the old source breaker must be tripped, the completion of the transfer to the new source should be blocked or possibly delayed to permit the new source to recover. In this latter case, transfer system logic could also be set up to provide transfer to an alternate new source.

Closed Transition - Hot Parallel Transfer

Prior to initiating a closed transition, hot parallel transfer, the voltage and phase angle difference between the motor bus and the new source must be evaluated to assure that the motor bus and the new source are in synchronism, and that the new source voltage is within acceptable limits. Due to dynamics that may occur prior to transfer, the two sources may not be in synchronism, or a large standing phase angle may be old between them, precluding a hot parallel transfer.
Additionally, control provisions must be incorporated such that, if the new source breaker is closed but the old source breaker remains closed, the transfer system must immediately trip the old source breaker. This allows parallel transfer but prohibits inadvertent parallel operation. The motor bus transfer design must ensure that a parallel condition is temporary to limit exposure to double-fed faults during parallel operation. Excessive fault currents under these conditions may violate the interrupting rating of circuit breakers or the through fault withstands rating of source transformers, and may damage other connected equipment. Thus, if there is a failure such that the old source breaker fails to trip, the new source breaker must automatically be tripped.

Hot parallel transfer cannot be used to transfer during transient or emergency conditions. If a transfer is initiated due to problems such as a fault on the old source, an open transition transfer method must be employed to first disconnect the old source that is problematic and then supervise the closure of the new source breaker.

Open Transition Transfer - Methods and Modes

There are three methods to supervise an open transition transfer and permit closure of the new source breaker when and if the conditions for a particular method are met:

- Fast
- In-Phase
- Residual Voltage

There are then two modes to initiate the process of closing the new breaker:

- Sequential
- Simultaneous

The three supervision methods are best displayed graphically by the three zones in the following figure of the voltage and phase angle decay of a motor bus during coast down after disconnection from the old source:

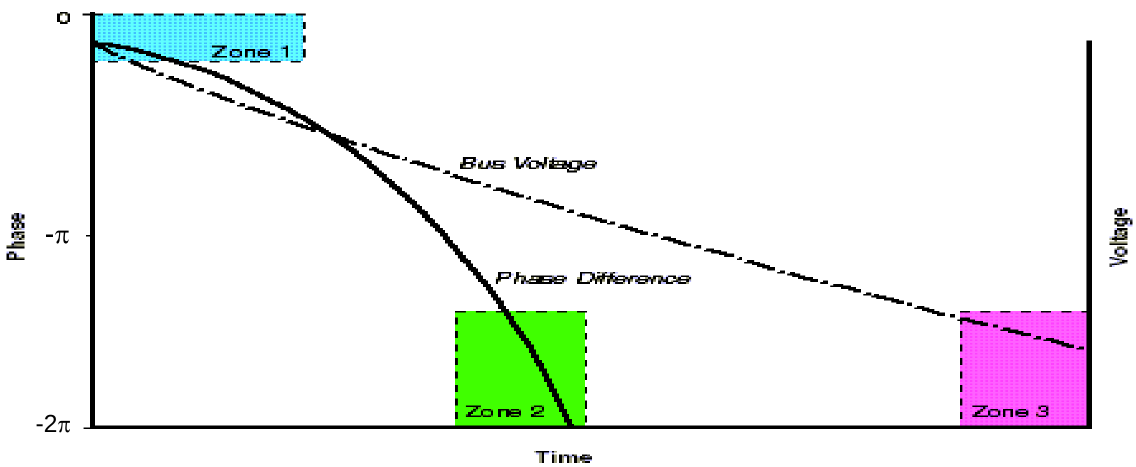


Figure 4 Open Transition Transfer Zones

Fast Transfer Method

The new source breaker will be closed by the Fast Transfer Method if the phase angle between the motor bus and the new source is within or moves into the phase angle limit of Zone 1. This method requires sync-check supervision, and possibly the use of a high speed sync-check device. Closing may also be supervised by an upper and lower voltage limit check on the new source to ensure its viability.

The bus transfer system must continuously monitor the conditions across the open new source breaker, including rapid changes in conditions due to phenomena that may occur prior to and during transfer. Thus, any rapid change in phase angle across the open new breaker entering or exiting Zone 1 prior or subsequent to tripping the old source breaker will result in an immediate action to permit or block the closing of the new source breaker.

Figure 5 illustrates this with two synchroscope pointers at the top of the dial representing two possible initial conditions. One is inside Zone 1 and would permit the new source breaker to close immediately, and the other is just outside and to the right. In this second case, as the motor bus decays after disconnection, the synchroscope pointer will always rotate counter clockwise as the motors are slowing down. Thus, the permission to close in this second case would have to wait until the phase angle enters Zone 1.

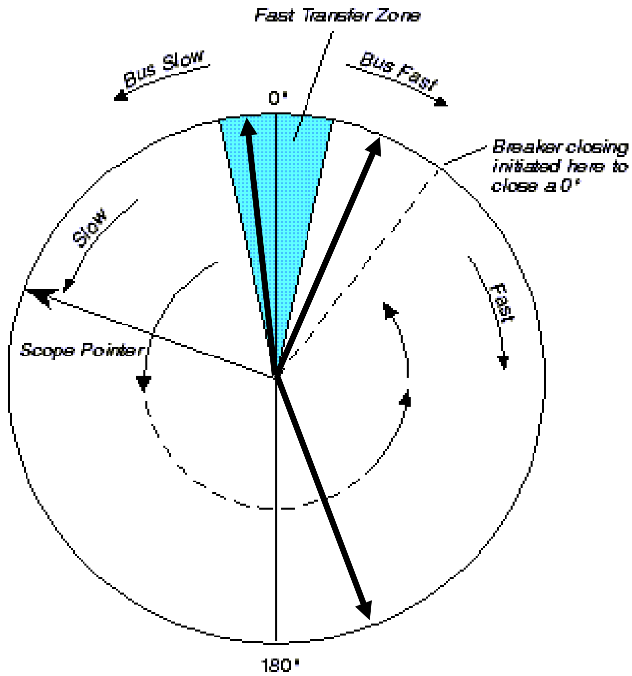


Figure 5 Initial Conditions Prior to Transfer

Presently, the majority of fast transfer systems are not supervised by high-speed sync-check relays. Standard sync-check elements typically have a minimum time delay of 0.1 second. By the time they respond to the phase angle of a decaying motor bus, the possibility of a successful transfer may have passed.

Worse yet, the contacts may still be closed and permit transfers at excessive angles, and thus subjecting motors to damage. Fast transfers are most safely performed with a high-speed sync-check relay specifically designed to supervise motor bus transfer.

In-Phase Transfer Method

The new source breaker is closed using the In-Phase Transfer Method by predicting movement toward phase coincidence between the motor bus and the new source. Closing is also supervised by an upper and lower voltage limit check on the new source and a slip frequency (ΔF) limit between the motor bus and the new source. The calculation of the predicted phase coincidence is compared with the breaker closing time setting for the new source breaker for the In-Phase Transfer method. In order to accurately predict phase coincidence, the device employed for the In-Phase Transfer Method must rapidly detect the decaying motor bus frequency, and the phase angle, slip frequency and change of slip frequency between the motor bus and the new source, to correctly compensate for the breaker closing time. High speed (half-cycle or less) response is recommended.

The purpose of this method is to continuously monitor the conditions across the open new source breaker, including the rapid change in conditions due to phenomena that may occur prior to and during transfer. Thus, if the above conditions are met, this system is prepared to permit closing of the new source breaker so the breaker poles are closed at the first pass through zero degrees.

The previous Figure 5 demonstrates this with the synchroscope pointer at the bottom of the dial representing a possible initial condition which is significantly outside any acceptable zone of closure. In this case, as the motor bus frequency decays after disconnect, the synchroscope pointer will always rotate counter-clockwise (ccw) as the motors are slowing down. Thus, the permission to close must now wait until the phase angle approaches the point of breaker-time-before-zero, marked by the dashed line on the synchroscope. This is the Zone 2 identified in Figure 4 where breaker closing is initiated for a close at 0 degrees.

Residual Voltage Transfer

The new source breaker will be closed by the Residual Voltage Transfer Method if the motor bus voltage drops below the Residual Voltage Transfer limit. This is the Zone 3 identified in Figure 4. Since this is unsupervised as to phase angle or slip frequency, this method must prevent closure of the new source breaker until the bus voltage drops below a predetermined voltage limit (usually < 0.25 pu) to ensure compliance with the 1.33 pu V/Hz limit. On the other hand, medium voltage bus transfers must be completed before the bus voltage drops so low that the under voltage motor protection elements time out and trip the motors. Thus, the motor bus transfer undervoltage settings and response must be coordinated with motor undervoltage relay time to operate to prevent motor drop-out. At the low voltage level, where motors are held in with contactors, latching or dc-operated contactors are used to ensure that the contactors do not drop out. The set point accuracy and speed of response of the motor bus transfer undervoltage relay must measure and operate correctly at frequencies below nominal, and with a significant rate of change in voltage decay.

During the time necessary to wait for sufficient voltage decay, it is of concern that the frequency may have already decayed past the stall point of motors on the bus. Consideration must be given to necessary load shedding in this case, and also in the case where the new source cannot re-accelerate all bus motors simultaneously. Thus, a detailed analysis of plant process is required to determine the effects of such a residual voltage transfer. The effect of transient torque on motors during a transfer restart should be limited to starting torque, and the motor restart must be properly sequenced to prevent excessive voltage dip. In any case, an analysis may be required due to the possible length of motor supply interruption.

These factors prevent this method from being employed for planned transfers from the startup transformer to the unit auxiliary transfer during power plant startup.

The experience at a combined cycle plant highlights the effect of a failed residual bus transfer system. This power plant consists of two combustion turbines (70MW) and one heat recovery steam turbine (80MW). The auxiliaries for the steam turbine and the gas turbine are interconnected. Just before initiating a gas turbine trip, the protection system is set up to generate an initiate command to the transfer module. The lengthy transfer time of 140 milliseconds resulted in a voltage on the motor bus that was outside the under voltage and time settings of the relays on the motor breakers. The trip of the steam turbine auxiliary equipment resulted in the trip of the steam turbine.

Open Transition Modes to Initiate Closing the New Breaker

If the Sequential Mode is selected, the old source breaker shall be tripped immediately, but closure of the new source breaker shall be attempted only upon confirmation by the breaker status contact that the old source breaker has opened. Upon receipt of this confirmation, the Fast, In-Phase or Residual Voltage methods of transfer must be employed to supervise closure of the new source breaker.

If the Simultaneous Mode is selected, the Fast, In-Phase or Residual Voltage methods of transfer must be employed to supervise closure of the new source breaker without waiting for the breaker status contact confirmation that the old source breaker has opened. Thus, with the Fast transfer method, the commands for the old source breaker and the new source breaker to trip and close could be sent simultaneously if and only if the phase angle between the motor bus and the new source is within the phase angle limit immediately upon transfer initiation. Otherwise, the old source breaker will still be tripped, but closure of the new source breaker must wait for conditions permitted by the Fast, In-Phase or Residual Voltage Transfer criteria.

Obviously, the Simultaneous Mode eliminates the time delay for breaker trip confirmation; however such a transfer must be supervised by a high-speed breaker failure scheme to avoid paralleling of the two sources if the old breaker fails to trip. As mentioned before, paralleling the two sources exposes equipment to double-fed faults. This clear disadvantage must be weighed against the need for speed for transfers of low inertia motors bus due to the rapid decay of frequency and voltage after the breaker is tripped.

VII. Industry Guidance:

In recent years, industry standards such as NEMA MG 1-2006 [D2] and National Electrical Manufacturers Association (NEMA) Standard, ANSI C50.41-2000 – "American National Standard for Polyphase Induction Motors for Power Generating Stations" [D3] have recommended as a guideline a limit of 1.33 per unit Volts per Hertz vector difference as a criterion to define a safe transfer of an induction motor bus and its connected loads from one source to an alternate power supply.

ANSI C50.41-2000, Paragraph 14, has an equation for the pre-closure Volts per Hertz as follows:

$$E_R = \sqrt{E_S^{\,2} + E_M^{\,2} - 2E_S E_M \cos\theta}$$

Where:

E_R is the resultant per unit Volts per Hertz across the open breaker.

E_S is the per unit Volts per Hertz of the new source to which the bus is being transferred.
E_S = new source per unit voltage ÷ new source per unit frequency
E_M is the per unit Volts per Hertz of the motor bus.
E_M = motor bus per unit voltage ÷ motor bus per unit frequency
Cos θ is the cosine of the phase angle between the new source and the motor bus.

The ANSI Standard contains the following graphical example:

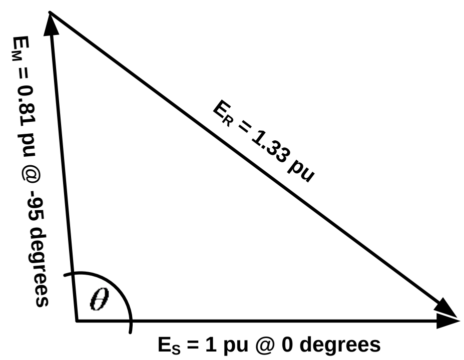


Figure 6 Vector Diagram from ANSI C50.41-2000 to Determine Resultant Volts per Hertz from Bus Transfer During Closing of New Source Breaker

The selection of the 1.33 pu V/Hz criteria was developed from studies which indicated that the resultant air-gap torque under the worst conditions was essentially the same as a single phase short circuit at the motor terminals. The effect of trapped flux in combination with the V/Hz criterion was considered.

The 1.33 pu V/Hz limit has become a common industry practice due to its ease of application and more importantly because it is the only criteria directly related to motor design. However, there also may be a need for a torsional study or computer simulation for the motor and connected mechanical system. Reference [D6] provides further details regarding studies and results.

<u>Resultant 1.33 Per Unit Voltage / Per Unit Frequency</u>

Reference [D3] addresses the requirements for polyphase induction motors with frame size larger than NEMA 440 series for use in power generating stations. Included are squirrel cage type, single speed or multi-speed, horizontal, or vertical construction, as well as form wound induction motors.

ANSI C50.41 is a NEMA standard, and is no longer listed under IEEE. The current status of ANSI C50.41 - 2000 is active. It should be noted that both NEMA MG-1 and ANSI C50.41 recommend analytical study of transient torques created by bus transfers. However, C50.41 recommends 1.33 per unit V/HZ as a conservative limit and an acceptable alternative to analytical studies.

C50.41, Section 14, Bus Transfer or Reclosing discusses the issues and concerns of out of phase reclosing. As is well known, this action can result in currents and torques that range from 2 to 20 times rated. The magnitude is a function of the motor's electrical characteristics, switching time, rotating system inertia, operating conditions, torsional spring constants, number of motors on the bus, etc.

Subsection 14.2 Slow Transfer or Reclosing suggests that: "the (bus transfer) system be designed so that the resultant Volts per Hertz vector between the motor residual Volts per Hertz vector and the incoming source Volts per Hertz vector at the instant the transfer or reclosing is completed does not exceed 1.33 per unit Volts per Hertz on the motor rated voltage and frequency bases." Seethe above Figure 6 for details on determining the vector relationships.

VIII. Dynamic Conditions During Bus Transfer

In order to adequately understand the issues related to the criteria for achieving a successful open transition bus transfer, one must first consider the conditions across the open alternate source breaker that will eventually have to be closed without causing damage to the motors or disruption to the process in which it is involved. One must consider conditions that may exist or events that may occur just prior to opening the initial source breaker to begin the transfer. These conditions or events affect the phase angle and frequency difference across the open alternate source breaker or the voltage of the alternate source. Furthermore, immediately after the initial source breaker is opened, other phenomena occur further affecting the phase angle and frequency difference across the open alternate source breaker prior to an attempt to close it to complete the transfer.

A. Events that occur or conditions that exist immediately prior to opening the initial source breaker

The voltage phase angle difference between the initial source and the alternate source can be substantial. This occurs for the reasons cited below.

The voltage phase angle across the open breaker, prior to transfer from the initial source to the alternate source, is affected by:

- Effects of a Fault
- Effects of an Out-of-Step (OOS) Generator Trip
- System Separation between Incoming Supply Sources
- Supply Source Transformer Winding Phase Shift

Effects of a Fault

- *Faults on the Initial source:* A fault on the initial source, in the case of the Unit 3 generator in Figure 7 on the 500kV bus, is the event that triggers the transfer. The type of fault (multi-phase or line to ground), the time the motor bus is connected to the faulted supply prior to transfer, and the proximity of the fault to the motor bus will effect a dynamic change in the phase angle across the new breaker just prior to transfer. In Figure 7, the 3-phase 500 kV fault causes a 29° phase shift to appear across the startup breakers from the alternate startup source fed from the 230 kV supply. Any dynamic phase angle change that appears across the alternate source breaker must rapidly be recognized by the motor bus transfer system. The synch check relays must be able to respond to the jump in phase angle and block an out-of-phase transfer, which could result in damage to the large hp reactor coolant pumps at transfer.

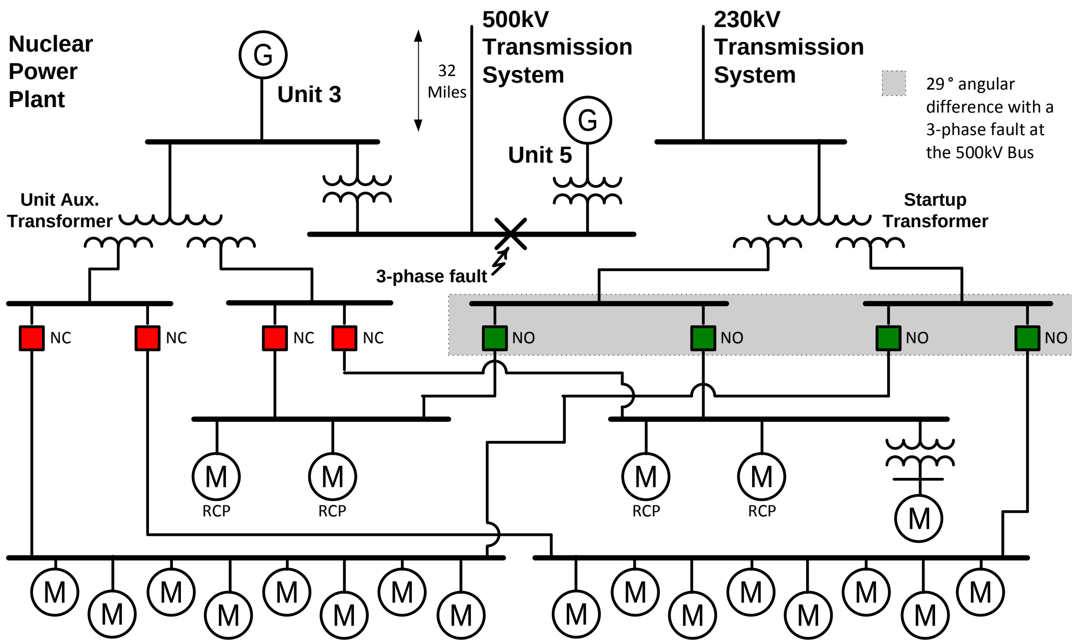


Figure 7 Faults on the Initial source

- *Condition of the Alternate Source:* The condition of the alternate source must be rapidly checked prior to transfer to insure that the events that triggered the transfer (such as a fault on the initial source) have not also affected the alternate source to the point where it is initially out of sync with the motor bus.

Effects of an Out-of-Step (OOS) Generator Trip

This example shows the effects of dynamic separation between sources in this case the generator and the system. As shown in Figure 8 below, the angular difference between the HV Bus & the Generator Terminals at the point of an OOS Trip will be the Motor Bus Transfer initial angle.

The Out of Step Relay (78) is provided to protect the generator from operating asynchronously with the power system. The 78 relay is typically programmed to trip when the generator internal EMF phase is between 120 to 240 degrees relative to the power system. This large internal power angle causes the phase angle across the Startup breaker to move to higher than expected values. The plot in Figure 8 shows how the

MBT starting angle can be affected by the variation of the generator internal rotor angle. (Note: This figure is an example and will vary depending on system parameters.) As shown in Figure 8 the starting angle can vary by greater than 30 degrees due to the pole slip of the generator.

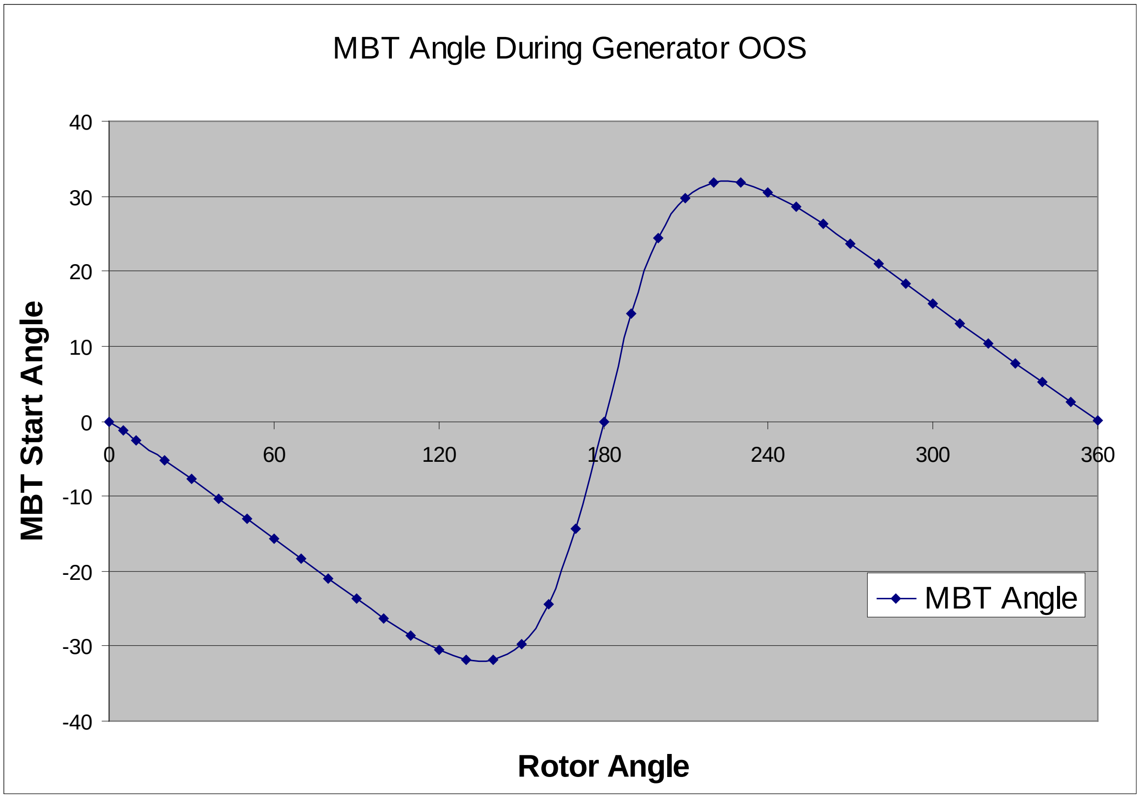


Figure 8 Effects of an Out-of-Step (OOS) Generator Trip

In a facility where the 78 relay would trip the unit breaker but not immediately trip the unit auxiliary breaker the phase angle of the motor bus voltage will change significantly due to the internal angle of the generator voltage at the point the unit trips. If the motor bus is left connected to the generator terminals, the motor bus voltage will jump quickly to a new phase angle due to the out of step angle of the generator internal voltage. This is due to the reactance of the generator relative to the equivalent reactance of the motors and the unit auxiliary transformer. The phase angle change will occur very rapidly since it is controlled solely by the generator internal voltage and the back EMF of the motors.

System Separation Between Incoming Supply Sources

- *Different Supply Voltages:* This phase angle difference is caused by supplying the motor bus sources from different voltages. For example, at power plants it is common that the unit auxiliary transformer (Source 1) be supplied from the generator terminals with the generator connected to an EHV (500kV, 345kV, 230kV) transmission system. The startup transformer (Source 2) may be connected to a lower voltage system (typically 161kV, 138kV, 69kV). This can result in a substantial voltage phase angle difference between the two sources since these two supplies come from different parts of the electrical system. Depending on the power flow characteristics between the two systems, this phase angle is constantly fluctuating. Furthermore, if the two systems become totally isolated, a slip frequency will develop across the alternate source breaker such that the voltage phase angle difference between the two sources could be significant when transfer is initiated.

- *Abnormal System Operation:* The abnormal operation of the power system can cause a large standing angle between the two sources to the motor bus. For example, the loss of an autotransformer that ties the systems together or the opening of breakers at a ring bus or breaker-and-a- half substation at a power plant can result in increasing the electrical separation between the two sources to the motor bus.

- *Loading of the Supply Transformers:* Under normal conditions one of the supply transformers (Source 1) to the motor bus supplies the entire load with the alternate source transformer (Source 2) unloaded. The reactive losses that result will cause a voltage phase angle shift between the two sources. This angular shift is generally much less than that caused by the abnormal system condition cited above. The loading of other upstream transformers that supply Sources 1 and 2 can also affect a phase angle shift.

Supply Source Transformer Winding Phase Shift

- ***Unit-Connected Generator Motor Bus with Wye-Wye or Delta-Delta Startup Transformer*** In typical applications, a wye-wye or delta-delta Startup Transformer connection is used, resulting in a net phase shift of zero between the Unit Auxiliary and Startup Transformers (see Figure 9). In this case Closed Transition (Hot Parallel) Transfers are possible and Open Transition Fast Transfers are permitted given sufficiently fast sync-check supervision and breaker speeds.

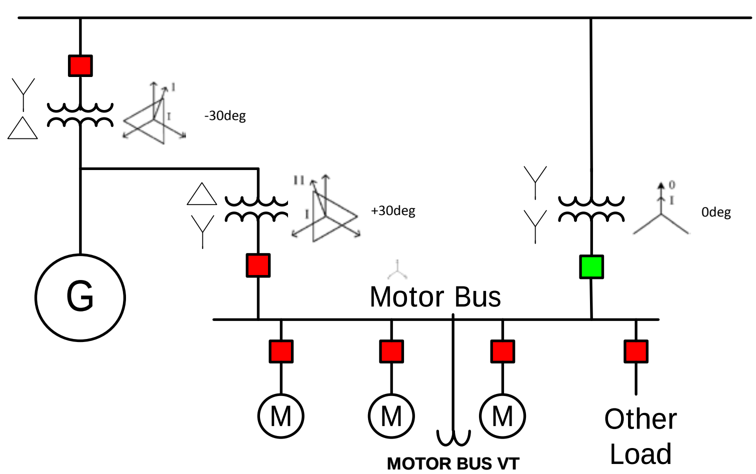


Figure 9 Unit-Connected Generator Motor Bus with Wye-Wye Startup Transformer

Unit-Connected Generator Motor Bus with Delta-Wye Startup Transformer: In some plants, a delta-wye Startup Transformer has been specified, creating a 30 degree phase shift between the Unit Auxiliary and Startup Transformers.

Startup to Unit Aux Transfer, Fast Transfer Possibility

The Startup Transformer source leads the Unit Auxiliary Transformer source by 30 degrees as shown in Figure 10. Hot parallel transfers are NOT possible. After the Startup Transformer breaker opens, the Motor Bus will begin slowing which moves the Bus voltage towards the Unit Aux Transformer voltage.

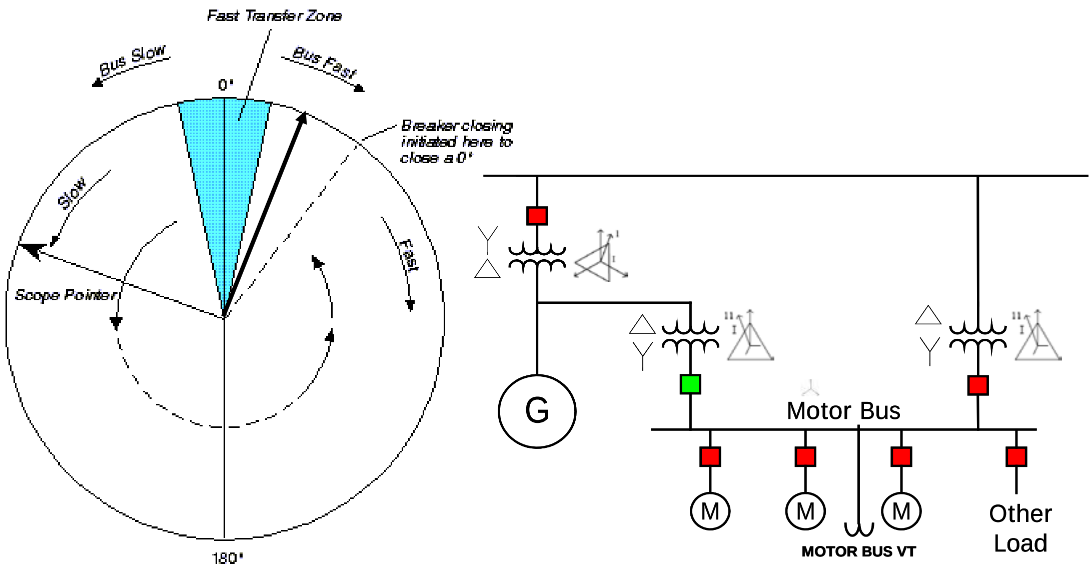


Figure 10 Unit-Connected Generator Motor Bus with Delta-Wye Startup Transformer - Startup to Unit Aux Transfer

Unit Aux to Startup Transfer, In-Phase Transfer Possibility

The Unit Auxiliary Transformer source lags the Startup Transformer source by 30 degrees as shown in Figure 11. After the Unit Auxiliary Transformer breaker opens, the Motor Bus will begin slowing which moves the Bus voltage away from the Startup Transformer voltage.

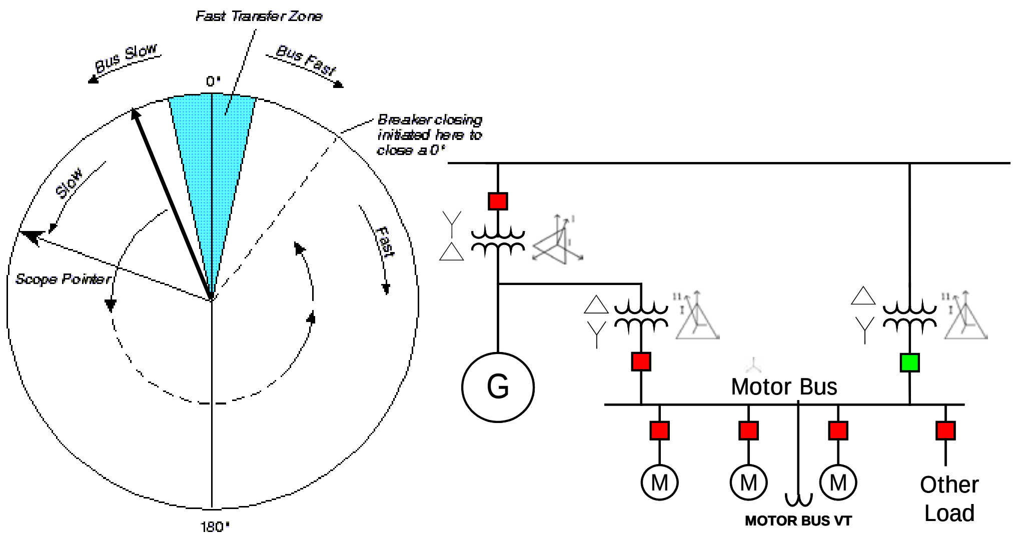


Figure 11 Unit-Connected Generator Motor Bus with Delta-Wye Startup Transformer - Unit Aux to Startup Transfer

B. Phenomena that occur immediately after opening the initial source breaker (52-1) but prior to closure of the alternate source breaker (52-2):

Transient Effects upon Disconnection of Motor Loads

Immediately following the opening of the initial source breaker, the mix of synchronous and induction motors on the disconnected bus develop a voltage on the bus that is determined by a number of factors. The first of these is the characteristic of induction motors whereby they exhibit an essentially instantaneous phase shift upon disconnect of motor. A simulation based on a 7,860 hp induction motor operating at full load supplied from an 11,550 Vac bus resulted in a nearly 10 degree instantaneous phase shift in the slow direction upon disconnect. This effect is additive to conditions occurring due to other causes, particularly upon disconnection following a bus fault. There have been reported cases of phase shifts on motors up to 20 degrees.

This effect is followed by a subsequent bus frequency decay, the speed of which is dependent on the combined inertia and loading of the motors connected to the bus.

Phase Angle and Bus Voltage Decay Characteristics

The phase angle rate of change across the alternate source breaker, caused by deceleration of the motors during transfer, and the rate of motor bus voltage decay are both determined by the type of motors in use and the type of loads being driven. This increasing rate of change of phase angle results in an increasing frequency difference between the motor bus and the alternate source.

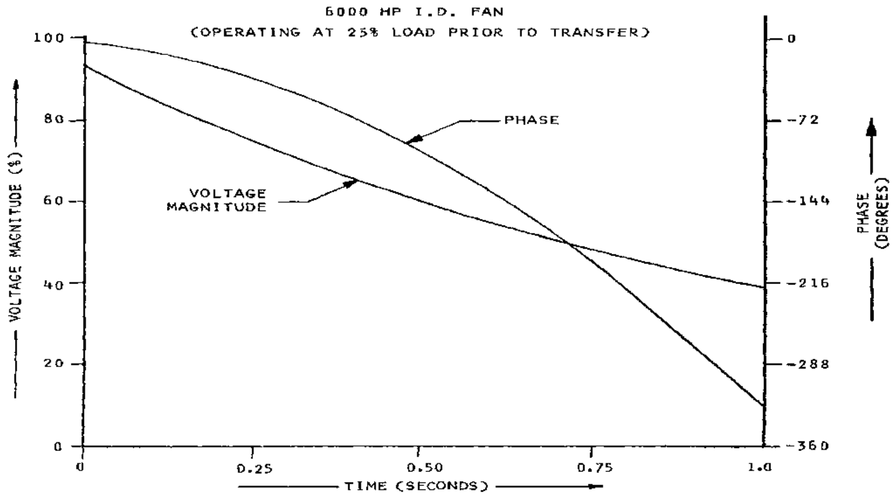


Figure 12 Coast Down of High Inertia Load on a Large Induction Motor

Some generalizations can be made as to the effect of motor type, size, and load characteristics on the frequency and voltage decay of the bus voltage due to the aggregate effects of the connected motors.

- *Motor Size:* The larger the motor, the longer the time the voltage will take to decay on an induction motor. (Number of poles)

- *Loading:* The higher the load on the motors, the faster the motor bus frequency will decay.

- *Inertia:* The higher the inertia of the aggregate motor loads on the motor bus, the more slowly the motor bus frequency will decay during the disconnected coast down period. This has a direct effect on how fast the phase angle changes. Low inertia loads will cause the phase angle to change quickly, as the frequency of motor bus decays quickly, and the slip frequency between the motor bus and the new source quickly increases (inertial stored energy).

- *Mix of Synchronous and Induction Motors:* Voltage will tend to decay much more rapidly on a motor bus with all induction motors. On a motor bus with a mix of synchronous and induction motors, the synchronous motors will attempt to hold up the voltage during the transfer interval.

C. The Role of Analytical Simulation, Field Testing and Engineering Judgment in Motor Bus Transfer

C-1 Analytical Simulation

Analytical simulation (modeling) by definition should result in the closest representation to what one should expect in a real world implementation of a transfer scheme and thus should be the preferred method; however, it is rarely used or implemented due to its cost.

Engineering simulations require mathematical modeling of the elements involved in the application (i.e. motors, loads, breakers, etc.) and a computer-aided analysis which allows changing of variables to predict the behavior of the system under different conditions.

In real world applications today, transfer schemes are usually developed using engineering judgment based on historical experience and testing. Field measurements are often used to develop the transfer system settings. Section C-2, C-3, and C-4 provide an example of these field measurements and analysis.

Key advantages of simulation over the use of engineering judgment are:

- Simulation requires using most variables of the actual application rather than a simple analysis based on a number of assumptions.
- Simulation provides a more accurate assessment of the response under different scenarios and helps define the operational limits of the application.
- A simulation mirrors the actual application and helps build confidence with users prior to the actual implementation of the transfer scheme
- A simulation transforms preparation and practice into genuine experience. This is particularly valuable for special or unique applications.

A computer simulation of the motor bus transfer can determine the response of the bus voltage magnitude and frequency after disconnection from its source. A simulation can also determine the phase angle between the bus voltage and the new source voltage prior to re-energizing the bus. Additionally, the current and electrical torque seen by the motor after the motor has been re-energized from the alternate source can be calculated. This information can be used to determine scheme type and setting requirements for the particular application. There are several software packages currently available that can simulate a bus transfer.

Detailed system information is required for an accurate simulation. For the motor, this includes nominal horsepower, voltage, frequency, stator impedance, rotor impedance, mutual inductance, inertia constant, friction factor, and number of poles. Some of this information is not directly available from the motor nameplate.
Another parameter that can be important for accurate simulation is the torque-speed characteristic of the load. Some loads have a torque characteristic that is relatively constant with speed. Other loads may have a torque characteristic that varies with the square of the speed. Furthermore, modeling a complex torque-speed characteristic within some simulation packages may not be a straightforward exercise.

Certain simulation packages offer multiple methods for calculation of quantities such as phase angle or voltage magnitude. Depending on the application, these methods can produce contradictory results. The chosen method should mimic the operation of the bus transfer relay. This implies some knowledge of the particular relay.
As with any computer simulation it is paramount to have a good idea of what to expect before modeling. For example, the references describe how to approximate the decay in

motor speed and voltage. The simulation results should be checked against such calculations to verify the model.

C-2 Spin (Ring) Down Testing

In conjunction with selection of the equipment necessary to implement an Open Transition Transfer Scheme, the engineer must first consider whether a particular motor bus, with its mix of motor size and types (induction and synchronous) and their connected loads, has sufficient inertia to endure the time required for a Fast or an In-phase transfer to be completed. This time is dependent on the speed of the breakers involved and on the equipment selected to monitor and control the transfer of the bus. Relays or systems must be considered that can make the necessary high-speed calculations to verify motor bus and new source voltage, frequency and phase angle differences, and then apply the Fast, In-Phase or Residual Voltage Transfer methods that will allow for motors and loads to be transferred without disrupting the process. Bench-testing may be necessary to verify the response characteristics of the transfer system components under consideration (see section IX. B. Dynamic Response of Relays Involved in a Motor Bus Transfer Scheme). If there is a possibility that the motor bus lacks sufficient inertia to permit a successful transfer with the transfer system components under consideration, the voltage, and frequency decay characteristics will have to be determined.

One of the most commonly applied methods to determine the inertia characteristics of a motor bus and estimate whether a Fast or an In-phase transfer scheme will be effective is by executing a spin down or ring down test. A spin down test involves tripping the motor bus at expected nominal conditions, thus disconnecting the motor bus from its source, recording the waveforms, and observing the frequency decay and voltage decay characteristics as the motors coast down. An analysis of the resulting oscillographic waveform determines whether the motors and loads on a specific bus have sufficient inertia to permit a successful Fast or In-Phase transfer with the equipment selected.

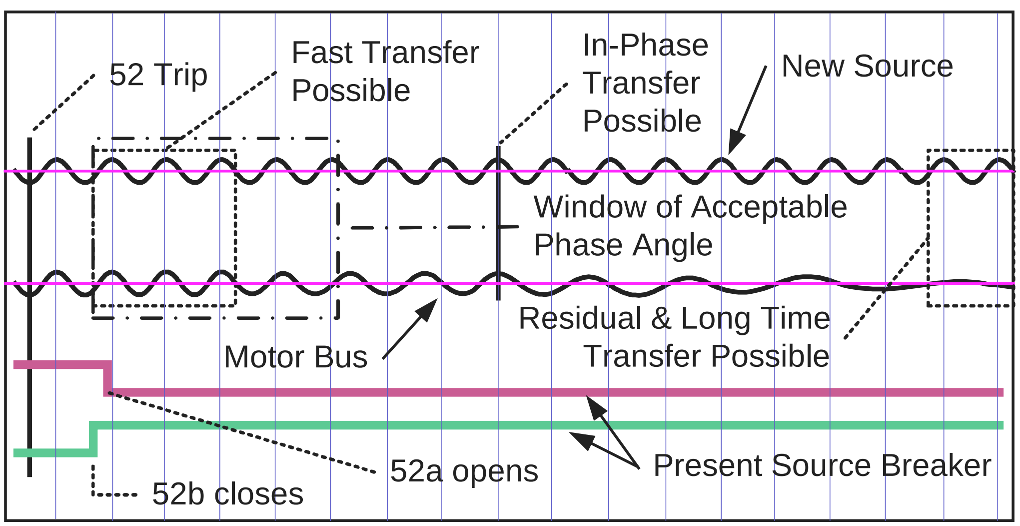


Figure 13 Spin Down Oscillograph Representation

However, it is quite likely that a spin-down test under expected nominal conditions, in other words with the plant on line or the process in operation, will not be allowed. Therefore, the spin down may have to be performed with the plant off line with only partial motor loads connected. The value of such a simulated spin down test with the generator off line is questionable due to the deviations between the frequency and voltage decay characteristics between a real spin down with the plant on line versus a staged test spin down with only partial motor loads connected. The spin down analysis performed in the following case study will demonstrate the significant differences of the decay characteristics of a staged test spin down versus a real spin down with the generator on line.

C-3 Field Acceptance Testing

If there is confidence in the dynamic response characteristics of the components to be used in the implementation of a transfer scheme, there may be no need to perform a spin down test prior to implementation of a transfer system. Engineering judgment, based on sufficient knowledge and experience in motor bus performance assessment, can be applied to a review of the mix of motor size and types and their connected loads. Furthermore, in such a case, a partial spin down analysis can actually be performed during the commissioning and field acceptance tests of a transfer scheme to determine the initial settings for voltage, slip frequency, and phase angle limits and to verify actual breaker operating times that must be taken into account in arriving at the settings and limits.

During such tests, the bus is tripped and then transferred to the new source, and the resultant V/Hz value, calculated at the point of the new source breaker closure, is monitored to assure that it is within the established maximum 1.33pu V/Hz criterion. The resultant V/Hz value can be used to decide if the safer Sequential Mode of transfer can be used rather than the Simultaneous Mode. Also, if this first test transfer is achieved by the Fast Transfer Mode, then a mathematical method can be used to extrapolate the predicted voltage and frequency spin down characteristics from the oscillography of the first few cycles of a fast transfer. This can be done with sufficient accuracy to verify that the frequency difference limit setting that would supervise an In-Phase Transfer is set above the actual slip frequency at the first phase coincidence so as not to block the transfer. It could also be employed to determine the setting and efficacy of a Residual Voltage Transfer as a backup method. The Residual Voltage Transfer setting must ensure that the motor bus voltage has not fallen too low at the point of the new source breaker closure, or the motors will be unable to accelerate. Conversely, the Residual Voltage Transfer setting must also ensure that the motor bus voltage is also not so high that an out-of-phase closure would exceed the established maximum 1.33pu V/Hz criterion. The new source breaker closing time must be considered to determine the voltage at the point of the new source breaker closure.

C-4 A CASE STUDY Motor Bus Transfer Spin Down Test

Project Background

The following case study uses actual data from commissioning tests of a Motor Bus Transfer scheme where the power company staged both a test spin down with the generator off line and partial motor loads connected, and a real spin down with the generator on line. Unit 1 is a 346.7 MVA generator with a three-winding auxiliary transformer feeding two separate 7.2kV buses. The startup transformer is also a three-winding transformer feeding two separate 7.2kV buses. There are a total of four generators with the same configuration at this site. A breaker close timing test had been performed, and the time was 5.40 cycles.

REAL SPIN DOWN TEST

Determine Viability of Sequential Transfer with Fast Transfer Method

It is initially assumed that the Fast Transfer Phase Angle Limit is set at 20°. Reviewing the oscillography, and assuming transfer initiates at the point in time when the “52b” breaker status contact closes, confirming that the initial source breaker has opened, the phase angle at that point is 4.3°, and a breaker close command would be sent by the Fast Transfer Method. The breaker close is 5.40 cycles later, and the per unit Volts per Hertz is calculated just prior to the breaker close. Note that the New Source (E_S) to which the bus is being transferred is 1pu Volts/1pu Hertz = 1pu V/Hz.

Oscillography Measurements at point of Breaker Close:
New Source = 116.0 Volts
Motor Bus = 90.7 Volts
Phase Angle = -49.2°
Delta Frequency = -1.67 Hz

Per Unit Volts Per Hertz Calculation:
Phase angle = 49.2°
Motor bus voltage pu = 90.7/116.0 = 0.7819pu Vrms
Motor bus frequency pu = (60-1.67)/60 = 0.9722pu Hz
E_M = 0.7819/0.9722 = 0.8043pu V/Hz
E_R = 0.7719pu V/Hz

This is well within the 1.33 per unit maximum Volts per Hertz defined by ANSI Standard C50.41-2000 Polyphase Induction Motors for Power Generating Stations.

As an indication of how rapidly the parameters are changing, it was noted on the oscillography that during the 5.4 cycles (90 ms) while the breaker is closing, the motor bus dropped 19.5 V, the Delta Frequency between the motor bus and the new source increased by 1.63 Hz, and the Phase Angle difference increased by 44.9°.

Analysis of Oscillography to Determine Settings Sequential Fast Transfer Setting Calculations

It was initially assumed that the Fast Transfer Phase Angle Limit is set at 20°. This setting is chosen because, one must consider the disconnect phase shift of induction motors and, if the transfer is initiated by a system disturbance or fault, there can be an instantaneous phase shift between the motor bus and the new source caused by the disturbance or fault. With this setting, an initial phase angle step change could occur across the new source breaker prior to the opening of the old source breaker, and the transfer scheme could still allow transfer.

For example, an instantaneous phase shift of 15.1°, for whatever combination of reasons, would have to be added to the 4.3° that was measured above after the old source breaker opens, resulting in an angle of 19.4°. This is just within the 20° Phase Angle Limit initially assumed for the Fast Transfer. We must perform an analysis to determine the effect of a close command issued at 19.4°. This worst case Sequential Fast Transfer breaker close is 5.4 cycles to the right.

Sequential Transfer Mode Fast Transfer Method - Worst Case

Oscillography Measurements, point at which Breaker Close Command is Issued:
New Source = 115.9 Volts
Motor Bus = 98.0 Volts
Phase Angle = 19.4°
Delta Frequency = -1.35 Hz

Oscillography Measurements at point of Breaker Close:
New Source = 115.9 Volts
Motor Bus = 83.7 Volts
Phase Angle = 72.0°
Delta Frequency = -2.01 Hz

Per Unit Volts Per Hertz Calculation:

Phase angle = 72.0°
Motor bus voltage pu = 83.7/115.9 = 0.7222pu Vrms
Motor bus frequency pu = (60-2.01)/60 = 0.9665pu Hz
E_M = 0.7222/0.9665 = 0.7472pu V/Hz
E_R = 1.0471pu V/Hz

This resultant per unit V/Hz is higher than the 0.7719 V/Hz calculated above for the normal Sequential Fast Transfer, but is just within the ANSI Standard C50.41-2000. Thus, a Fast Transfer Delta Phase Angle Limit setting of 20° is the maximum that should be considered.

Note that the Frequency Difference when the breaker close command is sent at 19.4 degrees is -1.35Hz, and that the Voltage Difference equals 115.9 - 98.0 or 17.9 V at the breaker close command. Also, note that during the 5.4 cycles (90 ms) while the breaker is closing, the motor bus drops 14.3 V, the Frequency Difference between the motor bus and the new source increases by 0.65 Hz, and the Phase Angle Difference has increased by 52.6 degrees. Thus, the Delta Frequency Limit setting must be set above 1.35 Hz so to not incorrectly block a transfer and, given the rapidly decaying frequency, must be set with enough margin to accommodate any change in the rate at which the motor bus frequency decays. Thus, a Fast Transfer Frequency Difference Limit setting of 2.0 Hz would be recommended.

With regard to any consideration of a Voltage Difference Limit setting, it is difficult to determine this setting under abnormal conditions because the location of a fault determines the effect it may have on the voltage. Since the motor bus voltage has not had much time to decay when the transfer is achieved by the Fast Transfer method, it is recommended that any Fast Transfer Voltage Difference Limit setting be disabled or be set sufficiently high to permit acceptable Automatic Fast Transfers. Note that any combination of maximum limit settings should always be inserted into the per unit V/Hz equation to ensure compliance with the standard.

Determine Viability of Sequential Transfer with In-Phase Transfer Method

Again assume transfer initiates at the point in time when the “52b” status contact closes, confirming that the old source breaker has opened, and then determine the conditions when a Sequential Transfer would occur by the In-Phase Method of Transfer at the first phase coincidence between the motor bus and the new source. The breaker close command would have been sent 5.4 cycles before this point.

Oscillography Measurements at point of Breaker Close:
New Source = 116.1 Volts
Motor Bus = 49.7 Volts
Phase Angle = 0.0°
Delta Frequency = -4.17 Hz

Per Unit Volts Per Hertz Calculation:

Phase angle = 0°
Motor bus voltage pu = 49.7/116.1 = 0.4281pu Vrms
Motor bus frequency pu = (60-4.17)/60 = 0.9305pu Hz
E_M = 0.4281/0.9305 = 0.4601pu V/Hz
E_R = 0.5399pu V/Hz

Again, this In-Phase breaker closure is well below the ANSI Standard C50.41-2000 maximum 1.33pu Volts per Hertz and indeed is a slightly better transfer than the best-case Fast Transfer.

It was noted on the oscillography that during the 5.4 cycles (90 ms) while the breaker is closing, the motor bus dropped 12.9 V to 49.7 V, the Delta Frequency between the motor bus and the new source increased by 0.83 Hz to 4.17 Hz, and the Phase Angle difference decreased by 126.4°. This clearly underlines the dynamic tracking accuracy and speed of response requirements presented by In-Phase Transfer applications. It is also noted that this very acceptable close can occur with a breaker close command sent 282ms after transfer was initiated by the breaker "52b" status contact.

Analysis of Oscillography to Determine Settings Sequential In-Phase Transfer Setting Calculations

The Frequency Difference Limit setting must be set for the conditions at the point in time when the breaker closes. As previously determined, the Frequency Difference between the motor bus and the new source, at the point of the new source breaker closure at the first phase coincidence, is -4.17 Hz, and the Frequency Difference Limit setting must be set greater than this. Since it was earlier noted that the Frequency Difference is increasing at a rapid rate of 9 Hz/sec, an In-Phase Transfer Frequency Difference Limit setting of 4.5 Hz would be recommended so as not to block a very smooth In-Phase Transfer.

In applications with high or medium inertia motor bus characteristics, the In-Phase Transfer method performs the transfer so that the breaker contacts would be closing at the phase angle zero crossing, so the per unit V/Hz at breaker closure is low. Thus, even though there is a larger voltage difference, it is preferred not to block the In-Phase Transfer with a Voltage Difference Limit. Also, it is difficult to determine the Voltage Difference Limit setting under abnormal conditions because the location of a fault determines the effect it may have on the voltage.

Furthermore, except under very low inertia motor bus characteristics, the In-Phase Transfer will always occur before the Residual Voltage Transfer opportunity, with a Voltage Difference that consequently is always less. With the ability to perform an In-Phase close, compared to the non-synchronous close of the Residual Voltage Transfer, the In-Phase Transfer is always preferable and does not need to be limited by a Voltage Difference Limit. In fact, per the per unit V/Hz equation, the In-Phase Transfer at 0 degrees will never exceed 1.00 pu V/Hz. It is recommended that any In-Phase Transfer Voltage Difference Limit setting be disabled.

Spin Down Analysis Sequential Transfer Mode
REAL SPIN DOWN SUMMARY versus TEST SPIN DOWN SUMMARY

A similar Test Spin Down analysis was performed and settings were determined. Note that the Test Spin Down, with the generator off line, and only partial motor loads connected, decays slower in frequency and faster in voltage than the Real Spin Down with the generator on line, and does NOT yield correct settings.

MOTOR BUS TRANSFER p.u. V/Hz CALCULATOR

INPUT
CALC
ANSWER

		REAL SPIN DOWN					
		FAST		**FAST WORST CASE**		**IN PHASE**	
	Delta Phase Angle =	49.2 Degrees		72 Degrees		0 Degrees	
	Cosine angle =	**0.6534**		**0.3090**		**1.0000**	
	V_S Voltage =	116 V		115.9 V		116.1 V	
	F_S Freq =	60 Hz		60 Hz		60 Hz	
Source E_S	**pu V/Hz =**	**1.0000 P.U.**		**1.0000 P.U.**		**1.0000 P.U.**	
	V_B Voltage =	90.7 V	0.7819 P.U. V	83.7 V	0.7222 P.U. V	49.7 V	0.4281 P.U. V
	ΔF F_B-F_S =	-1.67 Hz		-2.01 Hz		-4.17 Hz	
	F_B Freq =	58.33 Hz	0.9722 P.U. Hz	57.99 Hz	0.9665 P.U. Hz	55.83 Hz	0.9305 P.U. Hz
Motor E_M	**pu V/Hz =**	**0.8043 P.U.**		**0.7472 P.U.**		**0.4601 P.U.**	
Resultant E_R	**pu V/Hz =**	**0.7719 P.U.**		**1.0471 P.U.**		**0.5399 P.U.**	

FAST TRANSFER SETTINGS		IN-PHASE TRANSFER SETTINGS	
Delta Phase Angle Limit =	20.0 Degrees	Delta Frequency Limit =	4.5 Hz
Delta Frequency Limit =	2.0 Hz	Delta Voltage Limit =	Disabled
Delta Voltage Limit =	Disabled	Time Window =	120 cycles

MOTOR BUS TRANSFER p.u. V/Hz CALCULATOR

INPUT
CALC
ANSWER

		TEST SPIN DOWN					
		FAST		**FAST WORST CASE**		**IN PHASE**	
	Delta Phase Angle =	25.4 Degrees		52.5 Degrees		0 Degrees	
	Cosine angle =	**0.9033**		**0.6088**		**1.0000**	
	V_S Voltage =	116.7 V		116.6 V		116.7 V	
	F_S Freq =	60 Hz		60 Hz		60 Hz	
Source E_S	**pu V/Hz =**	**1.0000 P.U.**		**1.0000 P.U.**		**1.0000 P.U.**	
	V_B Voltage =	94.9 V	0.8132 P.U. V	87.3 V	0.7487 P.U. V	49.2 V	0.4216 P.U. V
	ΔF F_B-F_S =	-0.84 Hz		-1.21 Hz		-2.95 Hz	
	F_B Freq =	59.16 Hz	0.9860 P.U. Hz	58.79 Hz	0.9798 P.U. Hz	57.05 Hz	0.9508 P.U. Hz
Motor E_M	**pu V/Hz =**	**0.8247 P.U.**		**0.7641 P.U.**		**0.4434 P.U.**	
Resultant E_R	**pu V/Hz =**	**0.4361 P.U.**		**0.8084 P.U.**		**0.5566 P.U.**	

TENTATIVE TEST SETTINGS	FAST TRANSFER SETTINGS		IN-PHASE TRANSFER SETTINGS	
These settings are not final.	Delta Phase Angle Limit =	20.0 Degrees	Delta Frequency Limit =	3.4 Hz
Final Settings to be determined	Delta Frequency Limit =	1.0 Hz	Delta Voltage Limit =	Disabled
by tests under REAL operating	Delta Voltage Limit =	Disabled	Time Window =	120 cycles
conditions.				

Figure 14 Real Spin Down Summary and Test Spin Down Summary

IX. Application Issues and Concerns

A. Transformer Susceptibility to Damage Due to Bad Transfer:

IEEE Standards stipulate that power transformers are to be braced to withstand the maximum current experienced for a three-phase bolted fault on the secondary side with full primary voltage applied, or 25 times nominal current, whichever is less, for up to 2 seconds (refer C57.12.00-2006, clause 7.1.3.1). In other words, transformers must be built to withstand a per unit current as based on the following expressions:

$$I = \frac{1.0}{X_T}$$

where X_T is the transformer reactance or a reactance of 4.0%, whichever results in lower fault current. Figure 15 shows a power transformer connected between the utility system and the motor load. The value of fault current, I, that flows when the two systems are reconnected is,

$$\overline{I} = \frac{\overline{E}_S - \overline{E}_M}{\overline{X}_S + \overline{X}_T + \overline{X}_M}$$

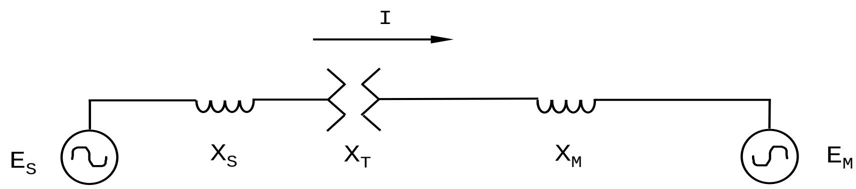


Figure 15 Transformer in path of out-of-phase system close.

This current should not exceed the transformer withstand current as discussed above. For example, the following system values will be assumed:

X_S = 3% on 100MVA base, 161kV
X_T = 4% on 30MVA base, 161kV
X_M = 15% on 7.5MVA base, 4.16kV

After converting to 100MVA, 161kV base: E_S = 1.0, E_M = 0.9 @ -180°, X_S = 3%, X_T = 13.33%, and X_M = 200.0%.

$$I = \frac{1.9}{0.03 + 0.1333 + 2.0}$$

$$I = 0.88 \text{ p.u.}$$

For the conditions above, the transformer experiences just less than 1 per unit current flow when the two systems are reconnected. In contrast, the maximum current for a bolted low-side three-phase fault is 6.1 per unit.

$$I = \frac{1.0}{0.03 + 0.1333}$$

$$I = 6.1 \text{ p.u.}$$

In this case, it is unlikely that the transformer will experience higher current when the two system are re-synchronized than it would for a bolted three-phase fault, but it should be considered and recognized that the likelihood increases with the size of the connected motor load and the phase angle between the two systems at time of reclosing. The above example is with a single 10,000HP motor. It can be seen that increasing the size or number of motors drives the denominator value down, increasing the current I.

B. Dynamic Response of Relays Involved in a Motor Bus Transfer Scheme:

Standardized testing can be performed on the various types and designs of Sync-Check and Undervoltage elements that are called upon to supervise and either permit or block transfer in the dynamic environment of motor bus transfers.

Test of Sync-Check (25) Function Response Time

The Motor Bus Transfer report published in 1993 by the Motor Bus Transfer Working Group of the IEEE Power System Relaying Committee (PSRC) states, "Using today's solid-state technology, high-speed sync-check relays have been developed that are accurate and fast enough to detect the change in relative phase angle between the disconnected bus and the alternate source. A fast bus transfer scheme utilizing a high-speed sync-check relay is classified as a "supervised" fast transfer." [D5] The following response tests were conducted on sync-check devices of differing technologies in an attempt to quantify what is meant by "high-speed sync-check".

Devices tested:
Analog Sync-Check Relay
Digital Sync-Check Relay
High-Speed Sync-Check Relay

Test Equipment:
Standard Relay Test Set

The following two tests were conducted and the results are given below:

Output Dropout and Pickup Test

The phase angle window is set at ±20 degrees setting and minimum (zero intentional) time delay for both the dropout test and the pickup test. The phase angle test results do not refer to a leading or lagging angle. In rotating machinery, where there is a slip frequency, degrees of angle on a synchroscope with negative values on the left (ccw) side of zero, representing a machine that is slow with respect to a fixed reference bus, as is the case when motors trip and decay in frequency relative to a source bus. Obviously, an actual synchroscope would not be able to correctly track the actual movements described in the following tests.
The reference to a synchroscope in Figure 16 is used as a conceptual tool only.

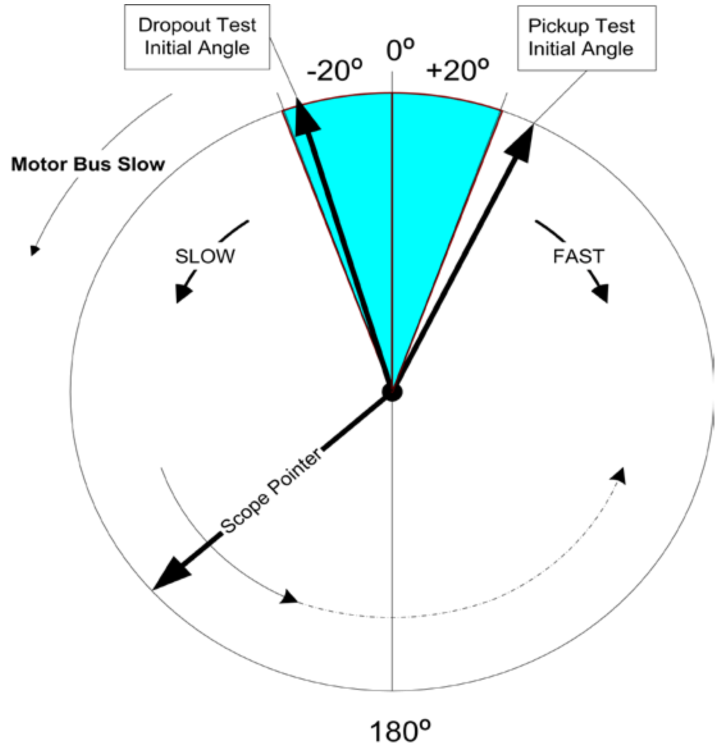


Figure 16 Conceptual Synchroscope

Dropout is defined as the point at which the output contacts change state (open).

In the **Dropout Test**, the initial applied input angle is set at -15 degrees, inside the phase angle window of 20 degrees, on the slow (left) side of 0 degrees on the synchroscope. The test is initiated by applying a linearly-decaying frequency and voltage, starting with 60Hz at 120 V applied to the MOTOR BUS input, leaving the SOURCE BUS input at 60Hz and 120 V. Since the contacts are initially picked up (closed), the test results will be displayed in phase angle at the point at which the output contacts change state as measured by the contacts opening to break the test circuit. Phase angle is measured on a scale of ±180 degrees ("+" to the fast (right) side and "-"to the slow (left) side of 0 degrees on the synchroscope).

Pickup is defined as the point at which the output contacts change state (close).

In the **Pickup Test**, the initial applied input angle is set at 25 degrees, outside the phase angle window of 20 degrees, on the fast (right) side of 0 degrees on the synchroscope. The test is initiated by applying a linearly-decaying frequency and voltage, starting with 60Hz at 120 V applied to the MOTOR BUS input, leaving the SOURCE BUS input at 60Hz and 120 V. Since the contacts are initially dropped out, the test results will be displayed in phase angle at the point at which the output contacts change state as measured by the contacts closing to make the test circuit. Phase angle is measured on a scale of ±180 degrees ("+" to the fast (right) side and "-"to the slow (left) side of 0 degrees on the synchroscope). If the contacts fail to close due to the high slip rate, this is displayed on the table as “No Close.”

Dropout Test

Motor Bus	Frequency Decay (Hz/sec)	Voltage Decay (V ac/sec)	Analog Sync-Check Degrees @ Dropout	Digital Sync-Check Degrees @ Dropout	High-Speed Sync-Check Degrees @ Dropout
High Inertia	8.33	75	-52	-24.4	-22.5
Medium Inertia	20	94	-58.6	-24.1	-23.2
Low Inertia	31	104	-170.6	-28.2	-23.5

Pickup Test

Motor Bus	Frequency Decay (Hz/sec)	Voltage Decay (Vac/sec)	Analog Sync-Check Degrees @ Pickup	Digital Sync-Check Degrees @ Pickup	High-Speed Sync-Check Degrees @ Pickup
High Inertia	8.33	75	4	15	19.8
Medium Inertia	20	94	No Close	14.5	18.1
Low Inertia	31	104	No Close	13.3	17.9

Dropout and Pickup Test Conclusions

The Analog Sync-Check relay is inappropriate for the supervision of a fast motor bus transfer. Even with high inertia motor bus characteristics, the dropout characteristics would permit a potentially damaging transfer at angles greater than 52 degrees when the breaker close time is considered. It would also incorrectly block opportunities for fast transfer as demonstrated by the Pickup Test results for motor buses with medium to low inertia characteristics.

Depending on its design, a general-purpose Digital Sync-Check device may have acceptable pickup characteristics for the given conditions of the test; however the dropout characteristics may preclude its use on fast transfer schemes on motor buses with low inertia characteristics. In any case, devices considered for application in fast bus transfer schemes should be tested to ensure acceptable performance.

The High Speed Sync-Check element, specifically designed for motor bus transfer applications, exhibits superior performance on both dropout and pickup for use in fast bus transfer schemes.

Blocking Phase Angle Test

The phase angle window is set at ±20 degrees setting with minimum (zero intentional) time delay. The tests are conducted starting at a zero angle and initiating a slip frequency as given in the table. Both positive and negative slip frequencies are used and the results are identical. The angles are given at the point the Sync-Check output contact opens.

Frequency Difference Hz	Electromechanical Sync-Check Degrees	Analog Sync-Check Degrees	Digital Sync-Check Degrees	High-Speed Sync-Check Degrees
0.05	27.18	22.1	20.3	20
0.1	40.32	23.8	20.6	20.5
0.25	54.00	28.7	23	21
0.5	73.62	36.7	25	21.6

Blocking Phase Angle Test Conclusions

It must be understood that the conditions for this test, with a step change in slip frequency, do not represent a realistic scenario for motor bus transfer applications. However, the rapid rate of change of slip frequency of the previous tests, even for a High Inertia Motor Bus, exceed the maximum slip of 0.5 Hz in less than 4 cycles, and the results for the electromechanical device would be meaningless due to its extremely slow response time. Thus this test is designed only to give an indication of the relative response of different sync-check devices.

The Analog Sync-Check is appropriate for generator synchronizing and system reclosing supervision applications where the applied slip frequency is low. However, for slip frequencies experienced during open transition motor bus transfer, the blocking angle is excessive. Thus, its use for motor bus fast transfer schemes is inappropriate.

It is also clear that the blocking phase angle for an Electromechanical Sync-Check relay would absolutely preclude its use for any motor bus transfer applications. The 1993 IEEE PSRC Motor Bus Transfer report comments: “In the past, fast transfer schemes have been implemented without a sync-check device and classified as “unsupervised” fast transfer schemes. Systems with induction disc sync-check relays have also been classified as unsupervised due to the poor performance and response time of an induction disc type sync-check relay for high-speed transfer conditions.” [D5]

The general-purpose Digital Sync-Check device has marginal dropout characteristics at an applied slip frequency of 0.5 Hz. Since slip frequencies experienced during open transition motor bus transfer easily exceed this level, the blocking angle of a given general-purpose Digital Sync-Check device may be excessive. Thus, its applicability for motor bus fast transfer schemes could be verified using the previous pickup and dropout Tests.

The High Speed Sync-Check element, specifically designed for motor bus transfer applications, exhibits superior performance as verified by the previous pickup and dropout Tests.

Test of Undervoltage (27) Function Response Time

The Motor Bus Transfer report published in 1993 by the Motor Bus Transfer Working Group of the IEEE Power System Relaying Committee (PSRC) defines Residual Voltage Transfer as follows: "A transfer scheme designed to monitor the magnitude of the bus voltage after the bus power source is removed and not to close the new source breaker until the bus voltage drops below a predetermined voltage limit." The following response test was conducted on the undervoltage element of sync-check devices of differing technologies in an attempt to quantify this response relative to use in such a residual voltage transfer application.

Devices tested:
Analog Undervoltage Element
Digital Undervoltage Element
Digital Motor Bus Transfer Relay Undervoltage Element

Test Equipment:
Standard Relay Test Set

Undervoltage Element Operate Test

The MOTOR BUS undervoltage pickup is set at 0.25 pu (30 V) and minimum (zero intentional) time delay for the operate test. In this test, an initial voltage of 1.0 pu (120 V ac) at 60Hz is applied to the MOTOR BUS input and the SOURCE BUS input with an initial phase angle of 0 degrees between the two inputs. The test is initiated by then applying a linearly-decaying voltage and frequency to the MOTOR BUS input, leaving the SOURCE BUS input at 120 V ac at 60Hz. If the Undervoltage relay used is a stand-alone device and not part of a sync-check package, then an initial voltage of 120 V ac at 60Hz is applied to the MOTOR BUS input, and the test is initiated by applying a linearly-decaying voltage and frequency to the MOTOR BUS input. Since the contacts are initially dropped out, the test results will be displayed as voltage at the point at which the contacts close to make the test circuit.

Undervoltage Element Operate Test

Motor Bus	Frequency Decay (Hz/sec)	Voltage Decay (Vac/sec)	Analog Undervoltage V ac @ Operate	Digital Undervoltage V ac @ Operate	Bus Transfer Undervoltage V ac @ Operate
High Inertia	8.33	75	23.7 V (0.20 pu)	27.5 V (0.23 pu)	30 V (0.25 pu)
Medium Inertia	20	94	22.4 V (0.19 pu)	26 V (0.22 pu)	27.9 V (0.23 pu)
Low Inertia	31	104	14 V (0.12 pu)	24.2 V (0.20 pu)	25.4 V (0.21 pu)

<u>Undervoltage Element Operate Test Conclusions</u>

In all tests but one, the voltage operating point was lower than the 30 V ac setting, due to the voltage element response time.

The change in the operate point for the Analog Undervoltage Element is significant, dropping 6.3 volts for motor buses with high inertia characteristics to 16 volts for motor buses with low inertia characteristics. At the medium voltage level, motors are switched with breakers and protected with time under voltage elements. To be effective, the under voltage element used to supervise a residual voltage transfer, must complete the transfer at < 33% voltage on the motor bus to comply with ANSI C50.41-2000, but before the motor protection under voltage element times out. Similar concerns exist at the low voltage level, where motors are held in with contactors, and latching or dc-operated contactors are used to ensure that the contactors do not drop out. With the above Analog Undervoltage Element characteristics, the coordination with motor undervoltage relay and contactor schemes to prevent motor drop-out would be difficult.

The range of operating points from 30 to 25.4 V ac range for the Motor Bus Transfer device from high to low inertia characteristics is slightly better than the 27.5 to 24.2 V ac for the general-purpose Digital Undervoltage Element. The operate points for the general-purpose device are slightly lower, but both devices would be appropriate to supervise a Residual Voltage Motor Bus Transfer.

Typical Frequency Response of Uncompensated E/M Voltage Relays

The following graph and table shows the typical frequency response of various types of uncompensated E/M voltage relays.

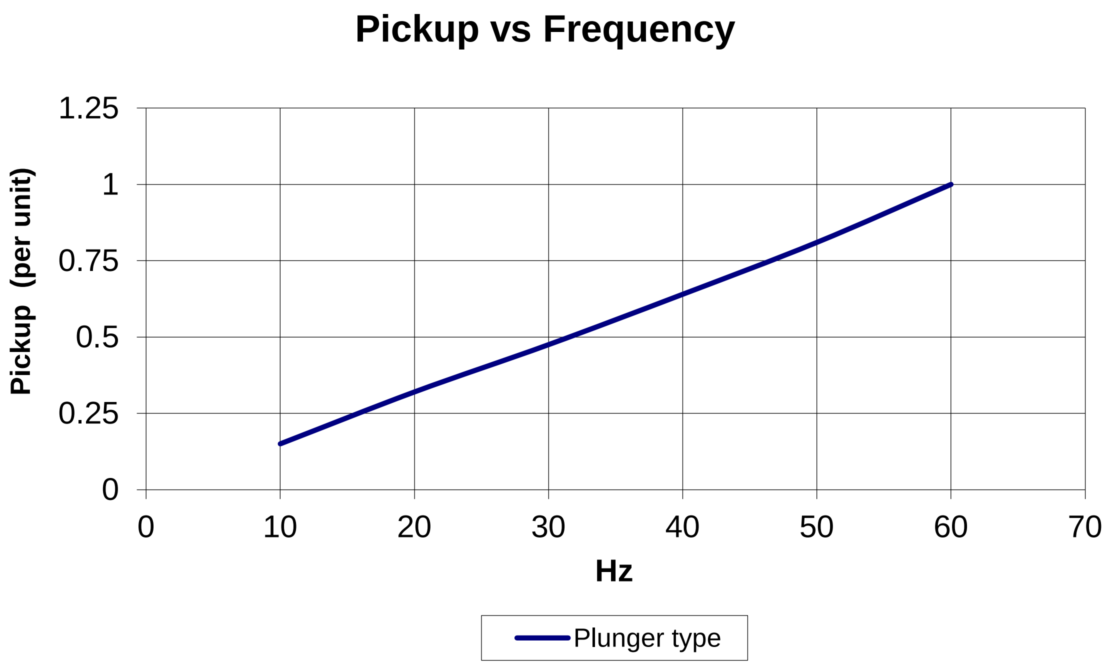


Figure 17 Typical frequency response of uncompensated E/M voltage relays

Fig. 17 shows the characteristic response for a plunger type relay, other designs will either over- or under-estimate the voltage when operating at off-nominal frequencies as shown in the table below:

Relay Type	Pickup (per unit)		
	30 Hz	60 Hz	90 Hz
Plunger/solenoid	0.5	1.0	1.5
Induction disk	1.6	1.0	0.9
Diode bridge rectifier	1.0	1.0	1.0
Hinged armature auxiliary	0.5	1.0	1.5

During a motor bus transfer, both frequency and voltage are changing quickly. Many undervoltage relay designs are unsuitable for this application as shown above. The protection engineer should check with the manufacturer to confirm that a particular relay is suitable for use in a motor bus transfer scheme.

C. Various Rationales for Shedding Load During Transfer:

The ability to shed non-essential loads may increase the chance of a successful bus transfer. The capability of an alternate supply source to accept the additional load of the transferred bus must be reviewed, considering the type of transfer employed. This is especially important where the normal supply source has an appreciable load prior to the bus transfer operation. The purpose of load shedding is to improve the chance of a successful transfer by eliminating unnecessary equipment and to minimize the stress placed on equipment during the transfer.

The high inrush of motors on the bus being transferred may cause unacceptable voltage and current transients on the new supply source trying to pick up the load. These in turn will affect performance of the resident loads as well as the performance of the newly transferred loads. Some equipment, such as low voltage ac contactors, may drop out if the voltage transient is severe enough. Tests have shown that some ac contactors can open for an 80% voltage transient lasting only 3 cycles. Shedding of certain non-essential loads could reduce the magnitude and/or duration of the transient voltage decay.

In a generating station, some of the motors are no longer needed following a unit trip. These can be safely shed while critical motors must remain connected. The relationship of the loads within a process must be considered when determining if they could be shed. For example, a relationship in a steam plant would be maintaining boiler air flow balance if an induced draft fan is tripped without tripping a corresponding forced draft fan. Plant operational preferences could include keeping a circulating water pump running to keep the condenser cool and keeping a boiler feedwater pump and condensate pump running to maintain water to the boiler to remove heat. Some motors, such as coal mills and conveyor belts may be safely shed; however they may create a nuisance for plant operations to restart if they have to be manually emptied. A review of the impact of shedding a motor should always be conducted.

The voltage magnitude and phase angle (as measured on the bus and related to the new supply source) is a composite of all loads connected to the bus. The normal diversity of bus loads includes both high and low inertia induction motors, static loads and possibly some synchronous motors. During the transfer process, high inertia motors will sustain their speed and therefore the phase angle relationship to the supply. The speed of low inertia motors will rapidly decrease, causing a large phase angle difference in relationship to the supply source. Since they will draw their power from the connected motors, static loads will decrease the bus voltage during transfer. Therefore, retaining high inertia motors and shedding low inertia motors and non-essential static loads would help keep the remainder of the connected loads closer to an in-phase relationship with the supply source. Because the shaft torque on a motor is affected by the voltage phasor relationship between the individual motor and the supply source, low inertia loads could experience greater shaft torque when the new supply voltage is applied at the time of the transfer breaker closure, due to the greater phase angle difference between the supply source and the individual motor. It was noted that synchronous motors must be considered, especially in paper and steel industries. There may be a need to trip large synchronous motors to avoid slipping a pole.

D. Impact of Motor Bus Transfer on Synchronous Motors

During a delayed bus transfer there is a period where the bus is not connected to either source. During this period the motors and attached loads will decelerate. When the bus is transferred to the new source the power from the new source will attempt to reaccelerate the motors back to operating speed. The synchronous motor is subject to going out of step with the power source due to the transfer. The system must be sufficiently strong to accelerate the motor back to synchronous speed prior to pole slipping occurring.

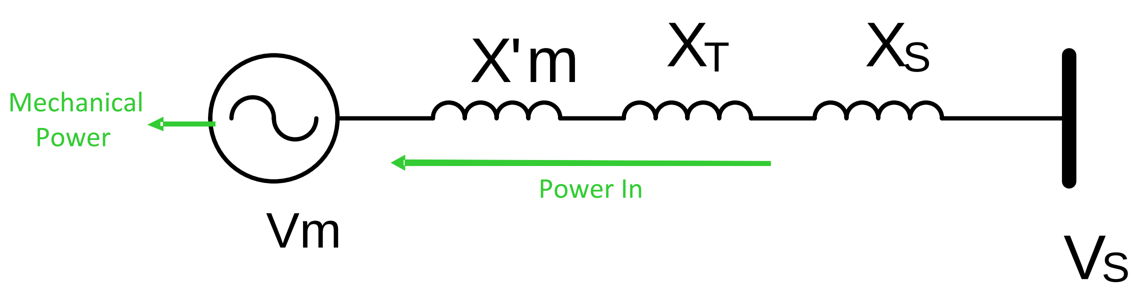
During the transfer, Fast or In Phase, the motor will decelerate. An angle will then develop between the motors internal voltage (Vm) and the system (Vs). (See Figure 18) When the motor is transferred to the new source the power from the new source must be sufficient to accelerate the motor back to synchronous speed prior to pole slipping occurring. After closing the new source breaker the angle will continue to increase until synchronous speed is obtained. If the angle increases to a point where the acceleration torque is below the load torque the motor will slip poles and become unstable. The motor must be tripped if this occurs.

The graphical "Equal Area Criteria" is typically used to determine the stability of a synchronous system, refer to Figure 19. The motor is initially operating at the point labeled "Operating Point." After the motor bus source is tripped the motor's internal angle will accelerate until the new source breaker is closed. The energy lost during this period is depicted as Area A1 in Figure 19. The energy to accelerate is shown as area A2. Area A2 must be greater than area A1 for the motor to remain stable. If the Max angle of area A2 exceeds the Max Stable angle the motor is unstable and must be tripped. The motor characteristic presented assumes no shunt motor loads connected or losses.

The Fast Transfer method minimizes the period of time that the motor is disconnected from the power source. This method provides the best opportunity to successfully transfer synchronous motors.

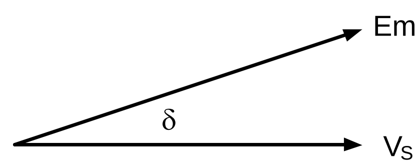
The In Phase transfer method delays the transfer until the motor bus voltage phase angle is back in sync with the new source and closes the new source breaker very close to phase coincidence. However there is much more motor deceleration during the transfer delay. The energy lost in the rotating motor is much greater than during a fast transfer. Detailed analysis should be done to ensure a stable transfer is possible before applying In Phase transfer to synchronous motors.

Stability Model



$$P = \frac{|E_M| \bullet |V_S| \bullet \text{Sin}(\delta)}{X}$$

Where: E_m = Internal Motor EMF under transient conditions
V_S = System Equivalent Voltage
X'_M = Motor Transient Reactance
X_T = Transformer Reactance
X_S = Equivalent System Reactance



V_M = Motor Terminal Voltage

$X = X'_M + X_T + X_S$

Figure 18

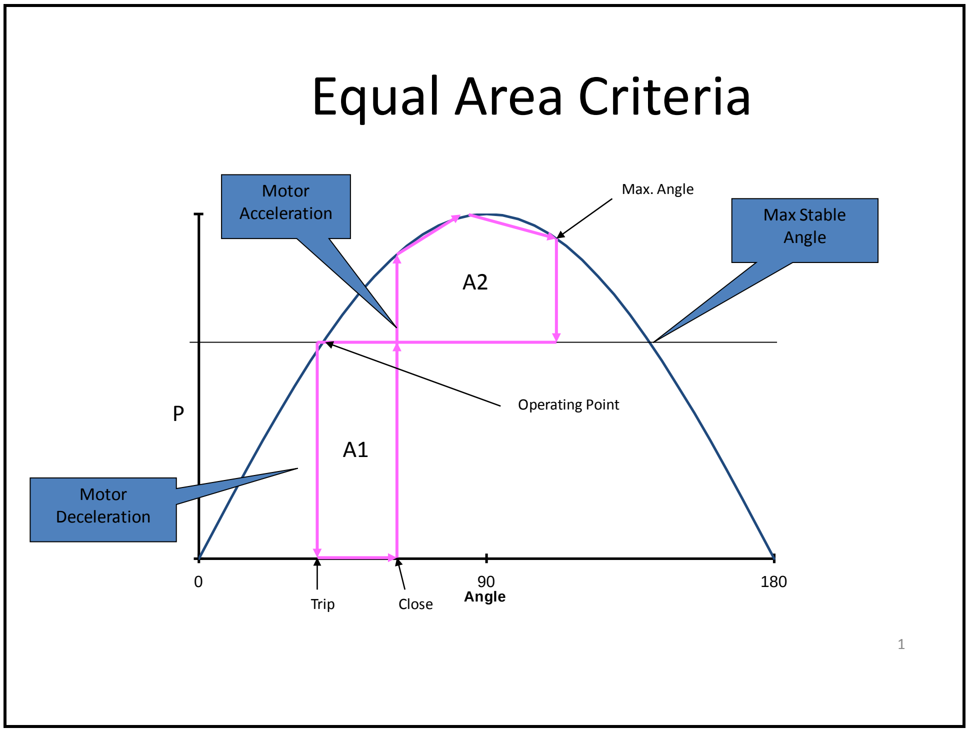


Figure 19

E. Collateral Effects of Transfers and Resulting Voltage Drops (i.e. Contactors Dropping Out on Critical Ancillary Equipment):

Care must be taken in the protection settings and control of all equipment attached to a bus that will be transferred under load. When a fast bus transfer occurs, momentary loss of voltage will occur. Modern multi-function motor protection relays have undervoltage settings with time delays. Control relays in magnetically held contactor circuits have sub cycle operating times, and magnetically held contactors can open as fast as 30ms. Transformer feeders may have low voltage motor control centers or other auxiliary equipment that need to be identified and prepared to ride through fast or even slow transfers.

Protection relays have two issues. The first issue is the undervoltage protection setting. Many modern relays have undervoltage protection with several adjustable setpoints. These settings may include but are not limited to undervoltage level, start delay and run delay. These settings need to be compared to the bus transfer scheme and set so the total system performs as expected. The second issue with protection relays is loss of voltage ride through. This information should be available in the relay manual or from the vendor. Some relays may be as short a 5ms while others can endure up to 250ms. If a transfer lasts longer than the published relay power supply ride through time, a undesirable operation may occur.

Motor control circuits in magnetically held contactors can be designed to handle loss of voltage or to restart after voltage is returned to the bus. The loss of voltage on a control relay can result in relay dropout in less than one half cycle. Control relays are often used to energize the main coil of a magnetically held contactor. When power is restored to a properly designed circuit the main interposing relay can re-energize and the main contactor would stay in the circuit. If the loss of voltage extends beyond the dropout time of the main contactor, a time delay undervoltage restart scheme must be employed to bring the motor back on line.

When motor bus transfers have additional equipment such as power transformers, the secondary loads must be investigated to determine what will happen during transfer. The transformer and additional cable will add impedance; therefore the overall voltage drop will be greater than at the medium voltage bus. The feeder device must have a control circuit that can withstand the momentary loss of voltage. The downstream devices, specifically low voltage motor control centers, need to be prepared to handle these momentary losses. Protection relays need to be adjusted to ensure the settings function as planned.

F. The Effects of Adjustable Speed Drives (ASDs) on Motor Bus Transfers:

The previous IEEE PSRC 1993 Motor Bus Transfer Working Group Transaction Paper discussed the issue of the effects of application of Adjustable Speed Drives (ASD) on motors connected to buses that are transferred. Due to the benefits of energy cost savings, removal of expensive and complicated mechanical flow controls, soft start capability, and the potential for reduction of the ASD motors contribution to short circuit currents, ASDs have seen more and more frequent application.

In the previous PSRC Working Group Report, three distinct operating strategies (schemes) for ASDs during bus transfers were identified and discussed as follows:

> "Scheme 1 – ASD system remains connected to the bus during bus transfer and continues to draw current from the motors on the bus. The result is a more rapid deceleration of the entire motor bus than the deceleration of the motor bus without an ASD system (motoring mode)."
>
> "Scheme 2 - The ASD is disconnected from the system during the initiation of the bus transfer and is reconnected after the restoration of the alternate power source (coast mode)."
>
> "Scheme 3 - The ASD system remains connected to the bus but is programmed to change the convertors to transfer energy from the rotating mass of the electrical machine and its connected load to the auxiliary systems. This helps to provide a forced deceleration of the mechanical equipment (regenerative braking mode)."

Salient points made in this paper for ASDs are:

A. These drive motors operate asynchronously with the system.

B. ASDs applied on the large high inertia applications do not provide support benefit to the other motor loads as the across the line type applications.

C. ASDs do not provide reactive power support to hold up residual voltage on the motor bus.

Please refer to this Working Group Transaction Paper for further details [D5].

IEEE Standard 1566-2005 – "IEEE Standard for Performance of Adjustable Speed AC Drives Rated 375 kW and Larger" [D4] provides guidance to the performance of the ASDs that can also be applied during bus transfers in the form of ride through capability and voltage sags. The following is a brief excerpt, Clauses 6.8 and 6.9 of this standard's performance requirement:

Clause 6.8 Voltage sags from [D4]:
"Unless otherwise specified, the drive system shall ride through and maintain control of the motor during a three-phase input power-supply voltage sag down to 65% of nominal on one or more phases for a duration of 500 ms as shown in Figure 2 extracted from [D4]".

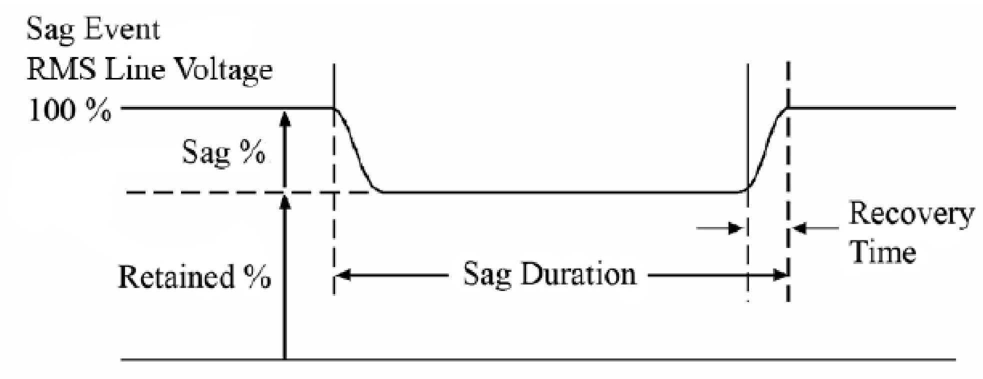


Figure 2—Voltage sag (figure not to scale)

Clause 6.9 Loss of voltage from [D4]:
"The drive system shall withstand a 100% loss of voltage in one or more phases of the input power supply for 2 s or longer without losing control capability. In this case, the drive shall cease output and, upon restoration of supply, shall have the capability to restart, catch, and reaccelerate the spinning motor to its original speed."

When applying drives and implementing a motor bus transfer scheme, engineers can use the requirements in IEEE 1566 as design performance criteria for their system. This will provide a basis for the drive performance during motor bus transfer.

As stated in the previous Working Group's Transaction paper, Motor Bus Transfer applications need to be studied and likely dynamically modeled when a motor bus system has a significant percentage (25% or greater total connected load) of ASD load connected. The volt per hertz limits of the motor loads need to be validated so that during transfer reasonable limits are maintained. A dynamic simulation of motor bus transfers using multiple operating ASD strategies (Scheme 1, 2, and 3) should be conducted to determine an acceptable approach. Typically, the larger motors and higher inertia motors are retrofitted or applied with ASDs due to the biggest economic and technical benefits.

As ASDs become a more prominent portion of the total connected load, these analyses become extremely important and necessary. In retrofit situations, ASD are usually added in stages, suggesting evaluation should be conducted at each stage.

G. Arc Flash Caution:

Arc Flash is primarily a personnel safety issue which must not be taken lightly. It is mainly concerned with operating and switching procedures along with personnel protective equipment and clothing. Companies implementing Motor Bus Transfer (MBT) may have maintenance procedures that allow personnel to work on a breaker in a MBT scheme while it is active, provided that the incident energy calculations have been performed to determine the type of Personal Protective Equipment (PPE) required working on it when energized. One alternative for consideration is to turn off the MBT during maintenance.

If the protection systems are equipped with controls to enable sensitive arc flash protection during maintenance activities, the arc flash protection should be enabled from both supply breakers during the maintenance. This will ensure that the protection is active in the event of a MBT.

Some basic design principles of a proper MBT scheme are the following:

- In general, since the MBT schemes are not designed to operate on current magnitudes, but rather on voltage and frequency, the MBT should be slower to make decisions than protective relays.
- If a motor bus fault occurs, a trip and lockout must be present to both source breakers, thus the MBT is not activated.
- If the source breaker is opened manually or by protective relay action, the MBT should not attempt to close the alternate breaker.
- The MBT scheme must be designed so that it can only issue a close to the alternate breaker if the MBT or other protective relay has initiated a trip of the normal breaker.
- If an operator closes the secondary breaker while the primary breaker is closed, the MBT should immediately trip the primary breaker assuming the operator intended to make a transfer, thus minimizing parallel time. (Possible alternative is an alarm indication "Sources Paralleled" if part of normal operation.)

- A failure of a load breaker on the motor bus must trip and lockout both the primary and secondary breakers, thus the MBT is not activated.
- If the MBT detects a problem and issues a trip of the primary breaker and it does not open, then the MBT must not close the secondary breaker, or must initiate breaker failure tripping.

If the MBT is designed with the above criteria, and proper Arc Flash Safety and Design is applied, this important issue can be managed.

X. Conclusion:

In summary, the Working Group has provided a basis for understanding the issues and concerns with the application of motor bus transfer systems. This document addresses issues, concerns, and recommendations for the proper application of Motor Bus Transfer Systems. As appropriate are included in the next revision of C37.96, IEEE Guide for AC Motor Protection.

The Working Group would like to thank all of the contributors to this effort both within and outside the IEEE Power System Relaying Committee.

XI. Annex

A. Case Studies Provided by Working Group Members

CASE STUDY - COMBINED CYCLE PLANT
"THE NEED FOR SPEED"

The following example shows actual data from commissioning tests at a combined cycle plant. This plant consists of two combustion turbines (154MW) and one heat recovery steam turbine (279MW). The plant auxiliary loads are noted below:

Bus A (4kV)	**Bus B (4kV)**
3600HP High pressure boiler feed pump	3600HP High pressure boiler feed pump
3600HP High pressure boiler feed pump	3600HP High pressure boiler feed pump
1100HP Condensate pump	1100HP Condensate pump
620HP Closed circuit Cooling pump	620HP Closed circuit Cooling pump
1500HP Gas compressor	1500HP Gas compressor
450HP Auxiliary cooling pump	1500HP Gas compressor
480V Service Transformers	450HP Auxiliary cooling pump
	480V Service Transformers

Note that these loads are centrifugal pumps and compressors. There are no fans or other high inertia loads in this application. In addition, the breakers are 35ms to trip and 60ms to close. This would be considered a medium-inertia motor bus and one that the industry in the past might consider a candidate for a simultaneous transfer. However, tests run at the plant during commissioning of a modern, high-speed MBT system reveal the following data:

Simultaneous Mode		***Sequential Mode***	
Transfer Time: (both breakers open)	24.2ms	Transfer Time: (both breakers open)	79.1 ms
Transfer Angle:	11.7 deg	Transfer Angle:	38.2 deg
Bus Voltage at Transfer:	98.2/120 V	Bus Voltage at Transfer:	77.8/120 V
Bus Frequency at transfer:	58.4 Hz	Bus Frequency at transfer:	57.8 Hz
V/Hz per C50.41-2000	**0.246 pu**	**V/Hz per C50.41-2000**	**0.629 pu**

The simultaneous mode is very fast, allowing a close at 11.7 degrees with the frequency decayed to 58.4 Hz and the voltage to 98.2 V ac. The resultant V/Hz is minimal at 0.246 pu. The sequential mode transfer was slower, which allowed the motor bus frequency and voltage to decay further to 57.8 Hz and 77.8 V ac. However the resultant V/Hz of 0.629 pu is still far below the 1.33 pu limit. Even in this application, which has less than ideal mechanical inertia, the sequential mode offers significantly more security without compromising the transfer. In applications with faster breakers, there will be even less difference between sequential and simultaneous operating modes. Using traditional sync-check relays, measurement time is much longer (up to 100msec). This long measurement time may prevent the scheme from detecting unacceptable conditions which could result in an improper transfer. In an attempt to minimize this effect, transfer systems using these slower devices are forced to operate at the highest possible speed, using the simultaneous mode. However, the safety of the simultaneous mode relies on a fast and reliable breaker failure scheme. Frequently, these schemes are assembled from auxiliary relays and wiring that are rarely tested. High speed sync-check measurement allows the luxury of employing the sequential mode to wait until the old source breaker is open before issuing the close command to the new source.

Conclusions:

- Worst case scenarios should be considered that include rapid external system changes, changes in loading that affect inertia, and the mixture of synchronous and induction machines.
- High Speed Sync-Check devices that are able to measure phase angle to pickup or block very rapidly if the angle moves in or out of the desired range excel at supervising fast transfers.
- Sync-Check relays used for traditional applications do not have the required speed of operation to effectively pickup or block if required.
- High Speed Sync-Check devices permit in-phase transfer that can determine the deceleration of the motor bus and effect a new source breaker closure at phase coincidence.
- The in-phase transfer mode offers an opportunity to synchronize a motor bus on the first available slip cycle. This type of transfer will maintain process continuity as the motors are still spinning, and the resultant V/Hz for an in-phase close is usually well below the 1.33 pu V/Hz maximum.
- Undervoltage relays traditionally used for residual voltage transfer exhibit setpoint error at low frequency that could permit an out-of-phase transfer well above the maximum acceptable resultant V/Hz limit of 1.33 pu.
- Undervoltage relays used should exhibit setpoint accuracy down to low frequencies.

B. Oscillography Examples from Working Group Members

Case Study – IEEE Working Group Report – oscillographic report and analysis

Thermal Power Plant

A bus transfer system is desirable for thermal power plants because it transfers all the critical auxiliaries to the healthy station source on the occurrence of a unit trip. Thus the unit can be restored quickly, reducing its overall down time. This faster recovery saves substantial losses in revenue as well as provides vital power generation and/or reserves in an expeditious manner.

The motor bus for the thermal power station auxiliaries is primarily characterized by the presence of large high-inertia fan loads such as forced draft and induced draft fans, and low inertia pump loads such as boiler feed pumps and cooling water pumps.

The spin-down characteristics in Figure B1 were obtained by tripping a lightly loaded unit at a 210 MW plant. It may be observed from Figure B1 that, due to the high inertia characteristics of the motor bus, the bus voltage and phase difference decayed gradually. The motor bus took 240 ms for the bus voltage to drop to 80% of its rated voltage and 146 ms to be more than 20 degrees out of synchronism with respect to its normal source before tripping. Thus, a fast transfer can be deemed suitable for a safe and smooth bus transfer operation with no interruption to the unit auxiliaries.

A simultaneous fast transfer of the unit is shown in Figure B2. The dead bus time for the unit was less than one cycle, which resulted in a safe and fast bus transfer with minimal loss of synchronism before re-energization.

Continuous Process Industry Auxiliaries

A bus transfer system is desirable for those continuous process industries with at least two independent sources of power where each plant trip results in substantial loss of material, production, and O&M costs.

The motor bus for continuous process industries cannot be singularly characterized, since each process demands different sets of motor configurations. However, typical installations consist of varying proportions of medium voltage (MV) and low voltage (LV) induction motor loads, compressor loads, pump loads, agitators, etc. Very often significant amounts of capacitor banks are connected to the bus for reactive power support for utility power factor requirements. These capacitor banks provide support to the bus voltage during the spin-down of the motor bus.

The spin-down characteristics in Figure B3 were obtained from live bus transfer trials under full-load conditions at a continuously operating PVC resin plant. The plant has two incoming 220 kV lines from different substations. The plant is susceptible to trips due to electrical faults, which are accentuated rainy climactic conditions in the region.

The 10.7 MW load consisted of a significant amount of low-inertia MV compressor load, along with other MV and LV pumps, fans, agitators, and other motor loads. An 8 Mvar capacitor bank was connected to the bus for power factor correction. It was observed that while the capacitor bank supported the bus voltage very well during the spin-down, the low-inertia load resulted in a rapid decay in bus frequency. The bus went through an entire slip cycle with respect to its alternate healthy source within 21 cycles. Due to this rapid loss of synchronism coupled with a sustained bus voltage, both fast transfer as well as in-phase transfer were deemed suitable.

Unlike the thermal power plant scenario where a unit trip signal was relayed to the MBT system, in this case the MBT system was required to self-detect the onset of a supply failure. Among several available criteria such as undervoltage, underfrequency, and df/dt, the instantaneous df/dt criterion was deemed best as the fastest indicator of loss of supply, requiring 3-4 cycles for detecting supply loss. For purposes of the live trial, the tripping of the 220 kV incoming breakers of the plant was done to induce the contingency.

A simultaneous fast transfer of this motor bus is shown in Figure B4. The total dead bus time of about 7 cycles includes about 4 cycles for the detection of supply failure and about 3 cycles for the closing of the alternate source breaker. The bus drifted by 60 degrees at a high rate of approximately 10 degrees per cycle before re-energization. The bus transfer was successful in maintaining the process continuity of the plant.

An in-phase transfer of the motor bus is shown in Figure B5. The in-phase transfer sent an advanced closing command to the breaker such that the breaker closed when the rapidly decaying bus was in near-synchronism with the alternate source, with 21 cycles of dead bus time before re-energization. The bus transfer was successful in maintaining the process continuity of the plant.

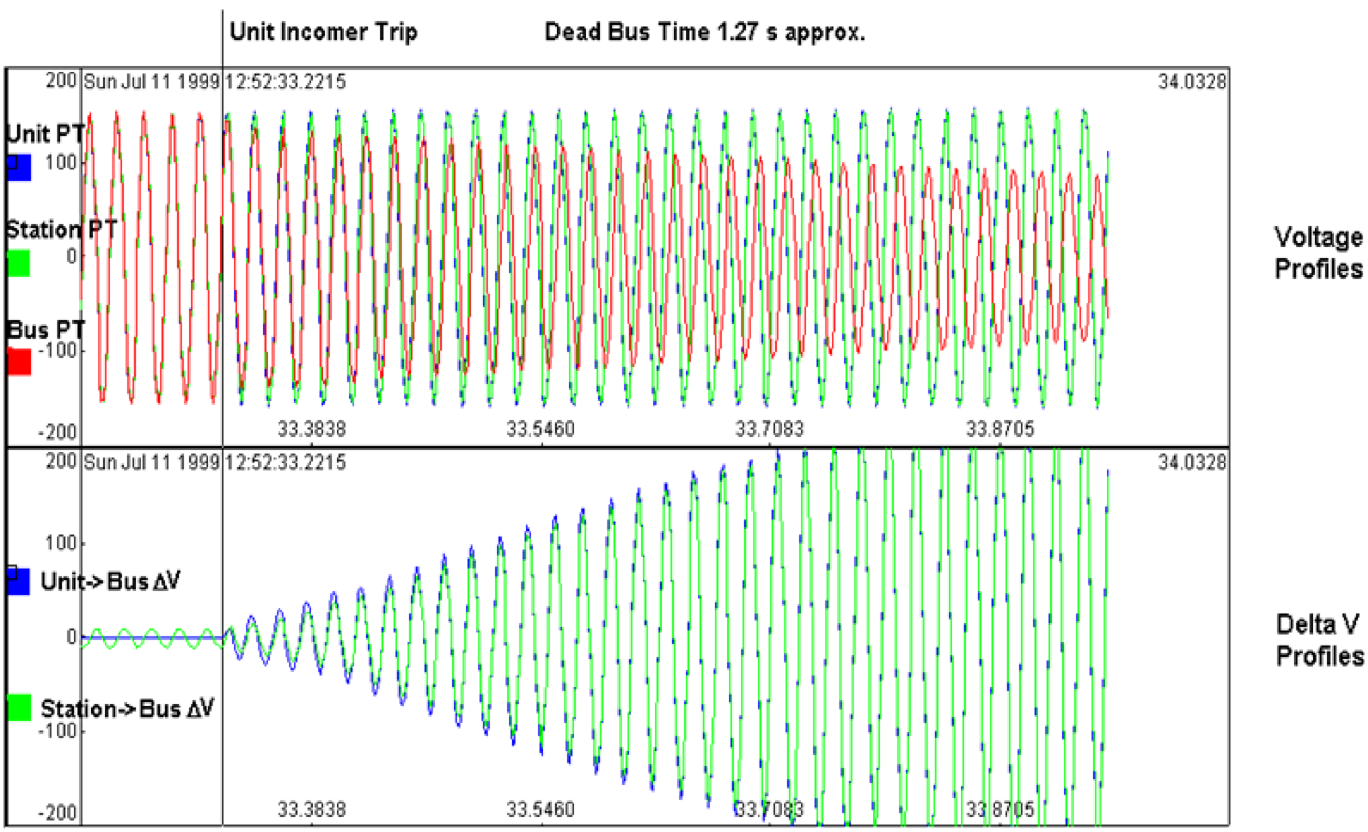


Figure B1: Spin Down Characteristics of a Thermal Power Station Unit Auxiliary Bus

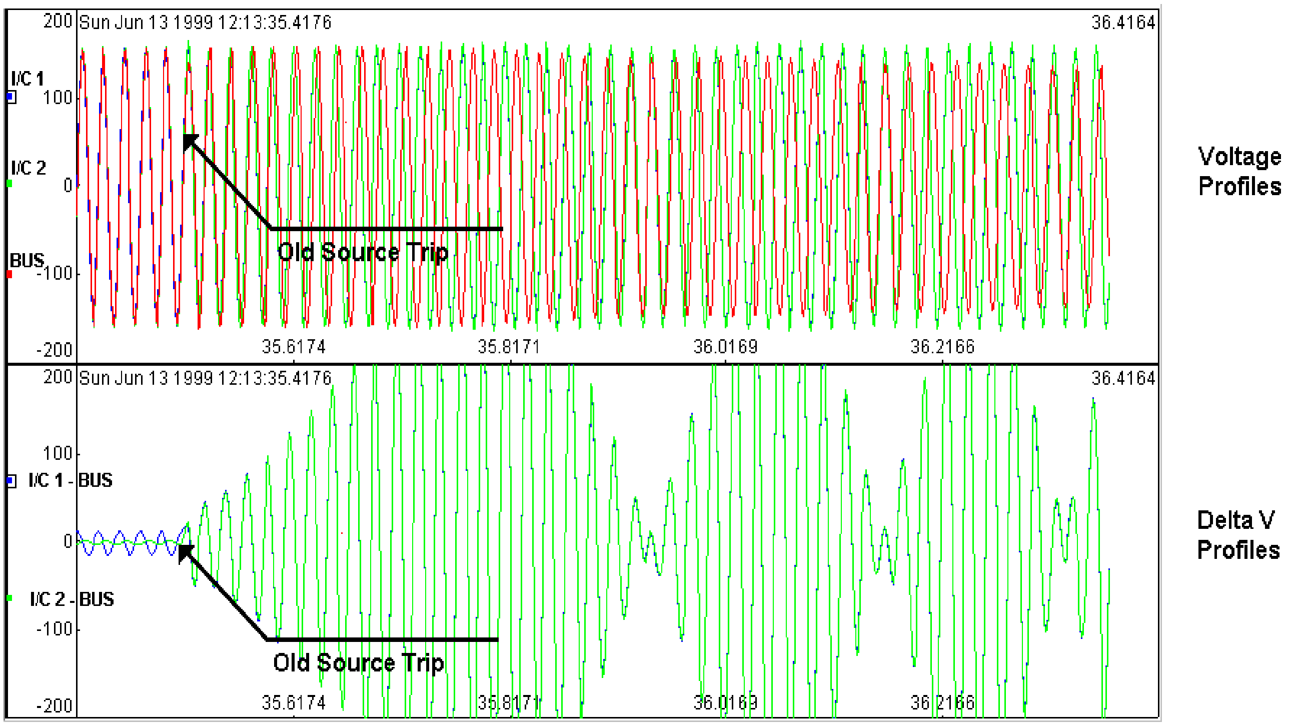


Figure B2: Fast Transfer of Unit Auxiliaries of a Thermal Power

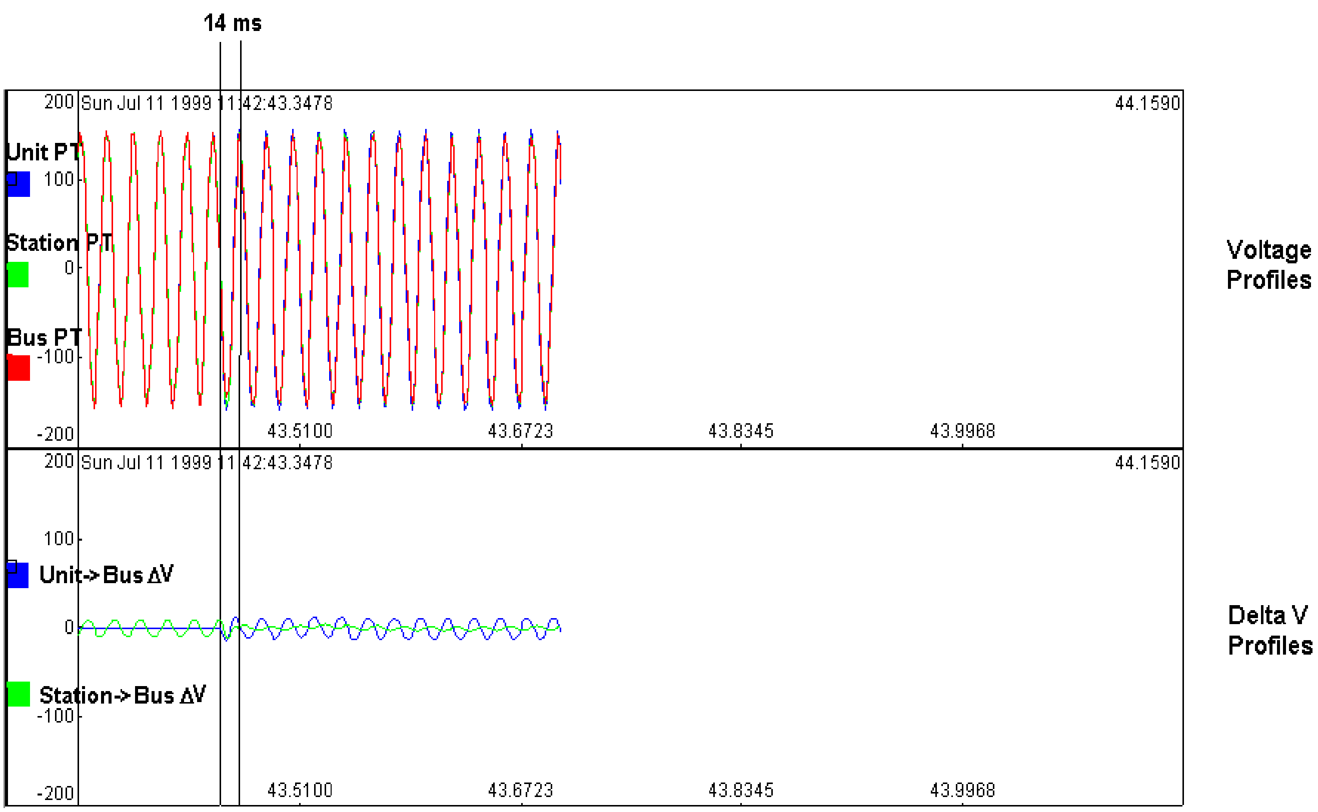


Figure 3: Spin Down Characteristics of a Process Industry Bus with Low Inertia Motors. (Voltage maintained due to presence of capacitor bank).

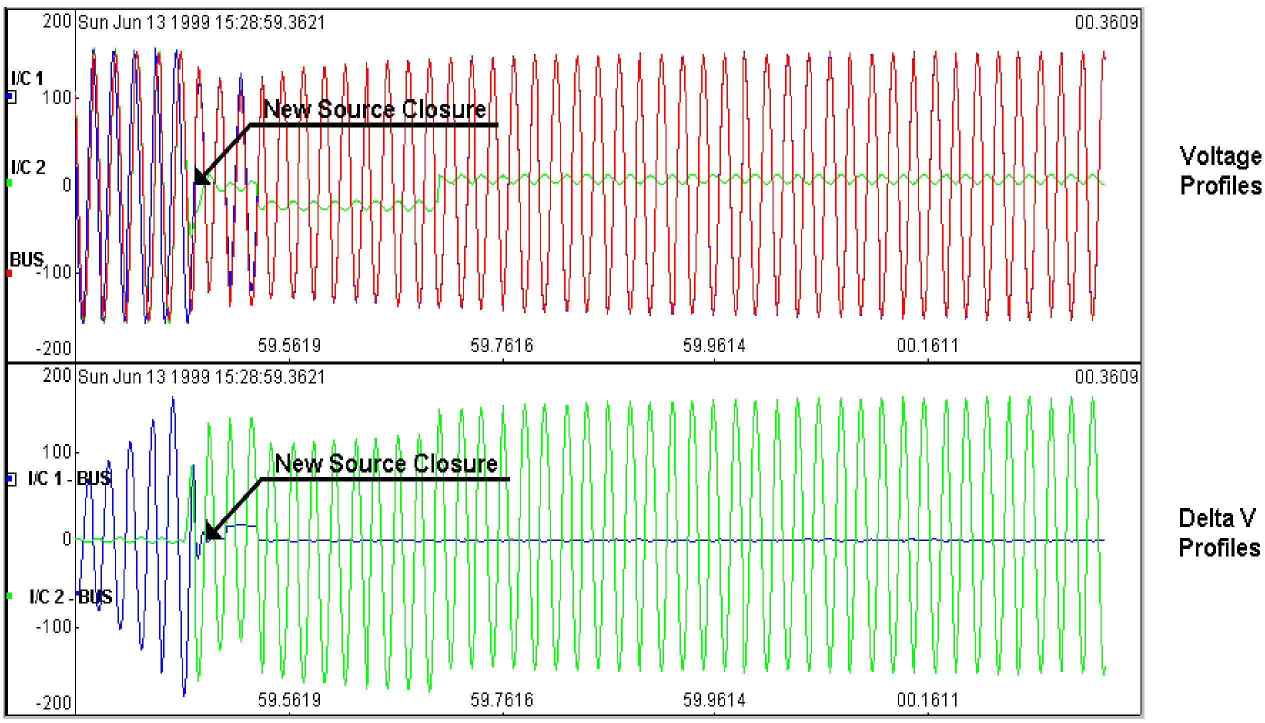


Figure B4: Fast Transfer of a Process Industry Bus with Low Inertia Motors within 6 cycles of loss of source initiated automatically on |df/dt| sensing.

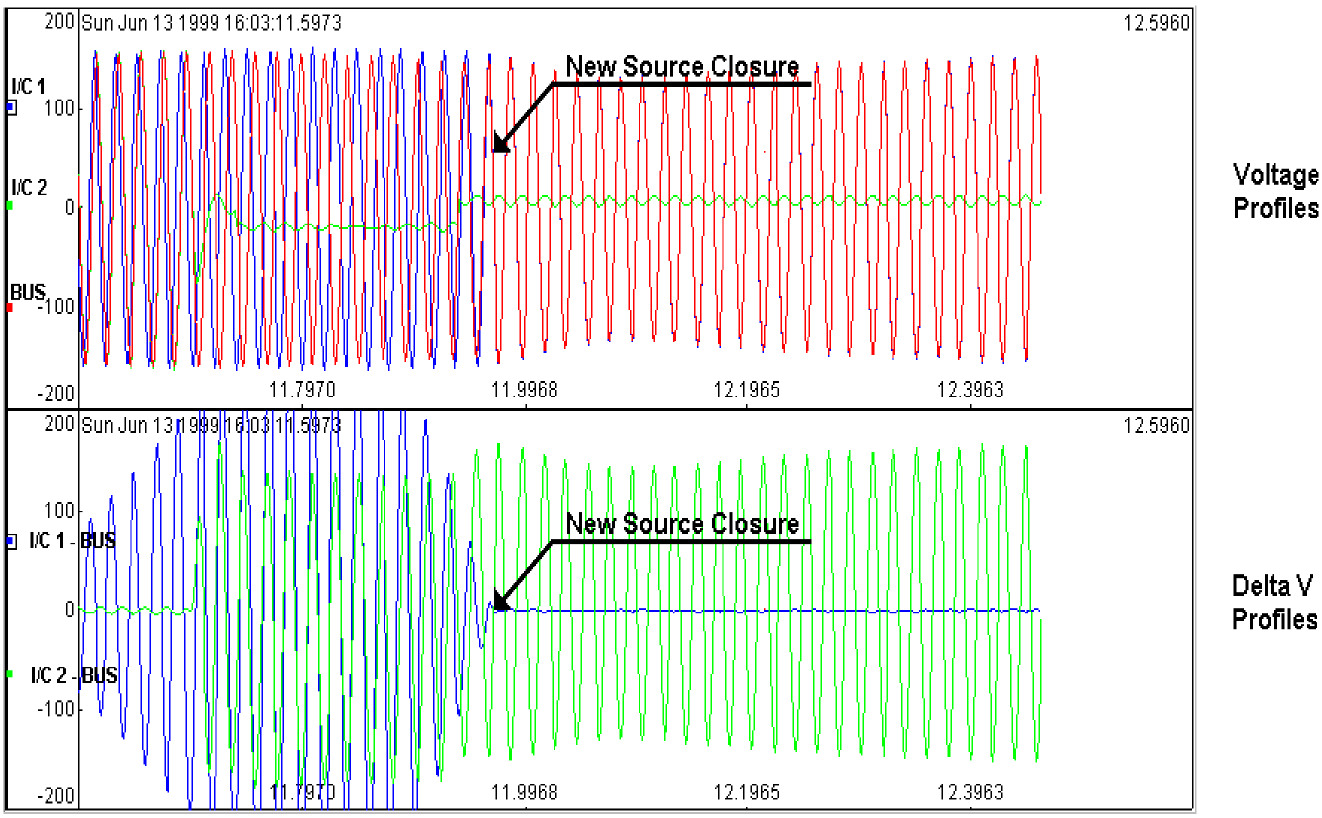


Figure B5: In-Phase Transfer of a Process Industry Bus with Low Inertia Motors within 21 cycles of loss of source initiated automatically on |df/dt| sensing. (Bus voltage > 85% due to capacitor bank).

C. Software Simulation Examples from Working Group Members

The Behavior of Motor Residual Voltage during a Transfer

The equivalent circuit for an induction motor is shown in Figure C1

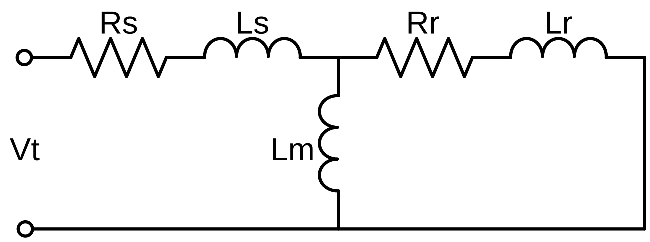


Figure C1

Where s and r denote stator and rotor quantities and Lm is the magnetizing reactance. When the motor is disconnected from the system, it will behave similar to a synchronous machine. A residual, decaying DC current produces a field in the rotor. This field induces an AC voltage in the stator. The magnitude and frequency of this voltage vary with the speed of the rotor. Equation 1 describes the voltage drop in the rotor circuit when the motor is disconnected from the system.

$$\left(L_m + L_r\right)\cdot\frac{di_r}{dt} + R_r \cdot i_r = 0 \qquad (1)$$

Solving for i_r:

$$i_r = i_{r0} \cdot e^{-t/T_0} \qquad (2)$$

And:

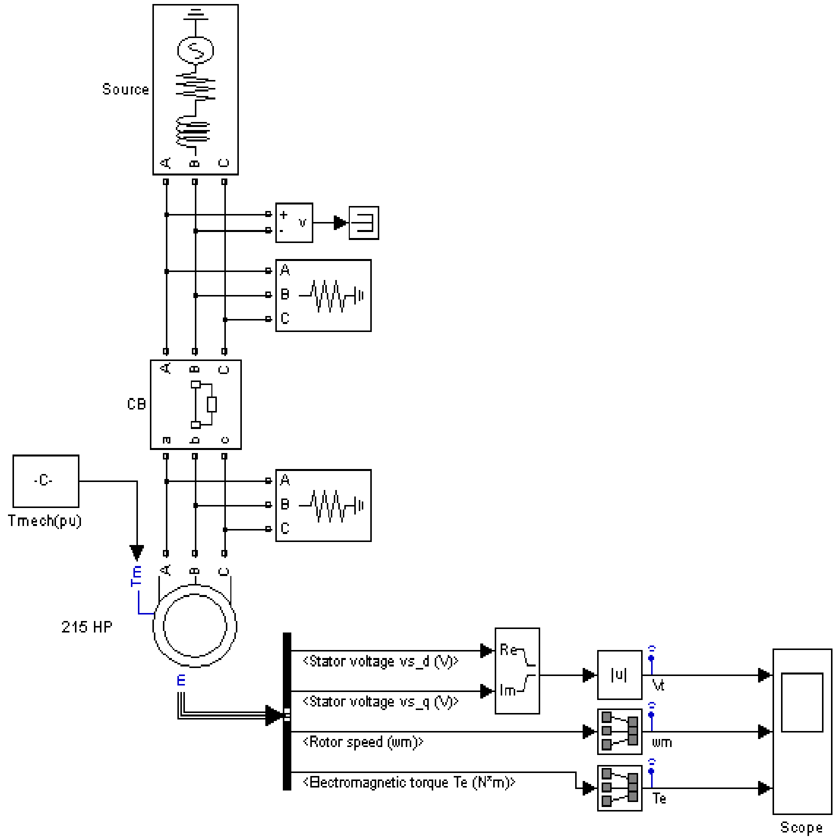
$$V_t = V_0 \cdot e^{-t/T_0} \qquad (3)$$

Where V_0 is the terminal voltage at the moment of disconnection and T_0 is:

$$T_0 = \frac{L_m + L_r}{R_r} \qquad (4)$$

Where T_0 is known as the open circuit time constant of the motor

The computer model of Figure C2 is used to investigate other impacts on motor residual voltage. The results are plotted against the open circuit time constant in Figure C3.



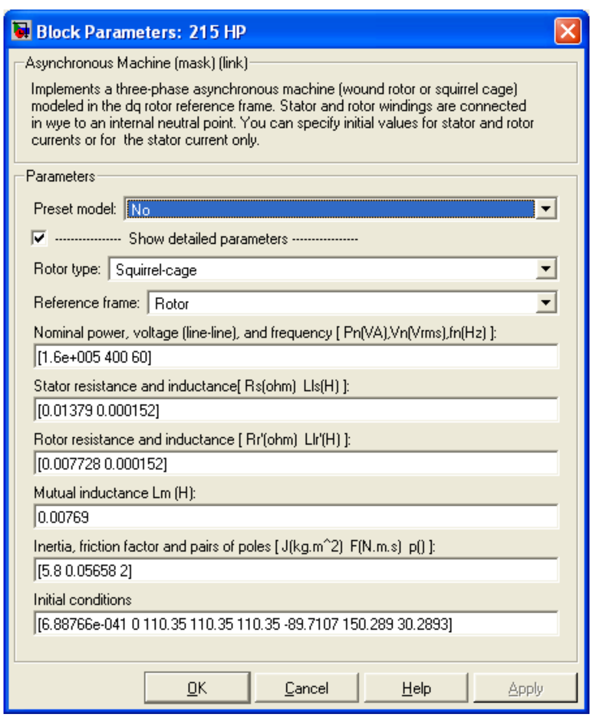


Figure C2 – Computer Model

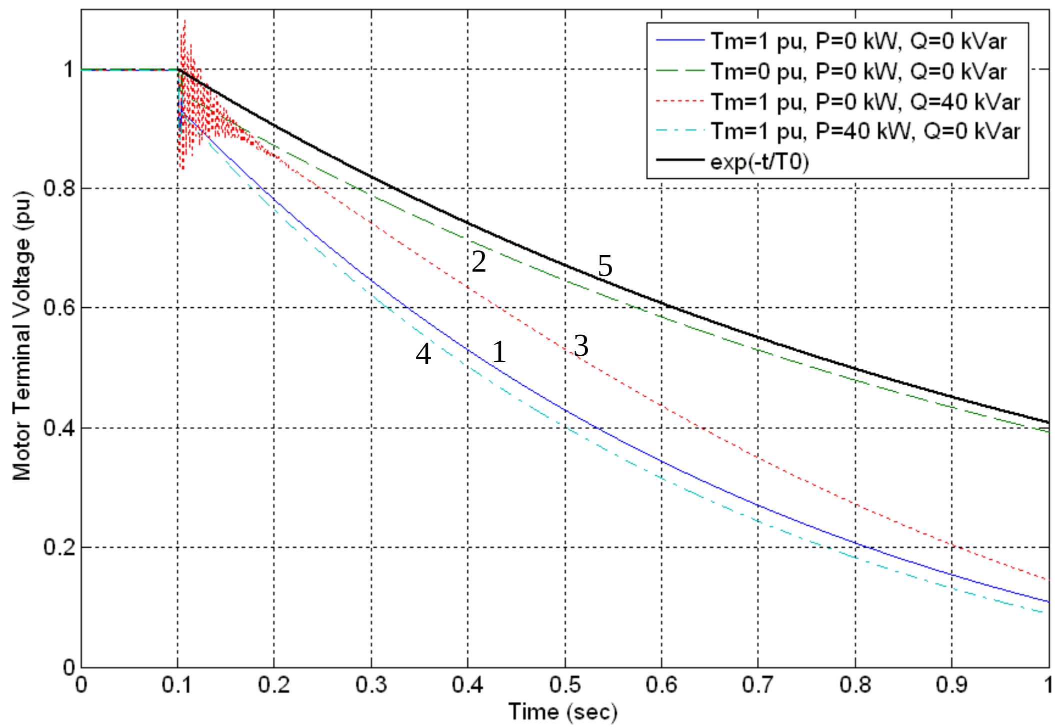


Figure C3 Motor Residual Voltage

Figure C3 Legend

Trace	Description
1	Rated mechanical torque is applied to the motor (T_M = 1 pu)
2	Mechanical torque is zero (T_M = 0 pu)
3	T_M = 1 pu & capacitance equal to 25% of motor rated power (power factor correction
4	T_M = 1 pu & a resistive load equal to 25% of motor rated power (power factor correction
5	Plot of $V_t = V_0 \cdot e^{-t/T_0}$ (the traditional method of determining voltage decay)

Note that trace 2 most closely approximates the motor terminal voltage as described by trace 5. There is significant difference between traces 1 & 2. This is due to the fact that the terminal voltage is also a function of motor speed and equation 3 does not take speed into account. Note that the motor speed will decay more slowly in motors with a higher inertia. Thus Traces 1 & 2 will more closely coincide.

In addition, impedances connected at the motor terminals will modify the circuit of Figure C1 and therefore will influence the rate of voltage decay. A capacitive load will reduce the rate of voltage collapse and a resistive load will increase it.

It can be concluded that the open circuit time constant provides a good approximation of the motor residual voltage if the motor speed does not decay substantially during the transfer and if significant impedances are not connected at the motor terminals.

This exercise also illustrates that when implementing a residual transfer scheme, it is better to measure voltage directly then to rely on a time delay based on the open circuit time constant of the motor. In general, measuring the voltage will allow a transfer to occur more quickly. [D39]

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