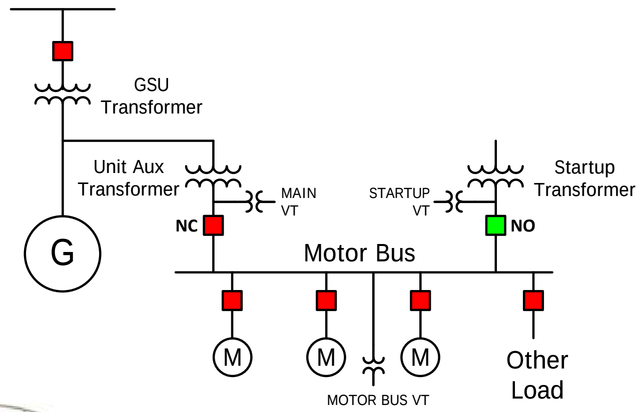
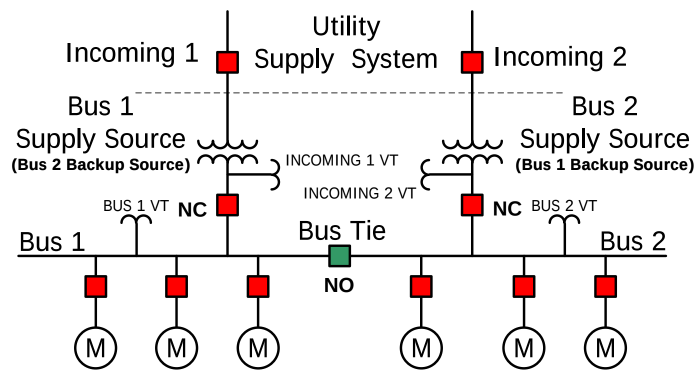
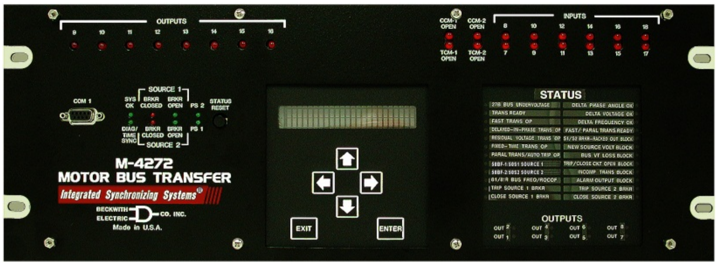
M-4272
Motor Bus Transfer System

Test Results for
Fast and In-Phase Transfers





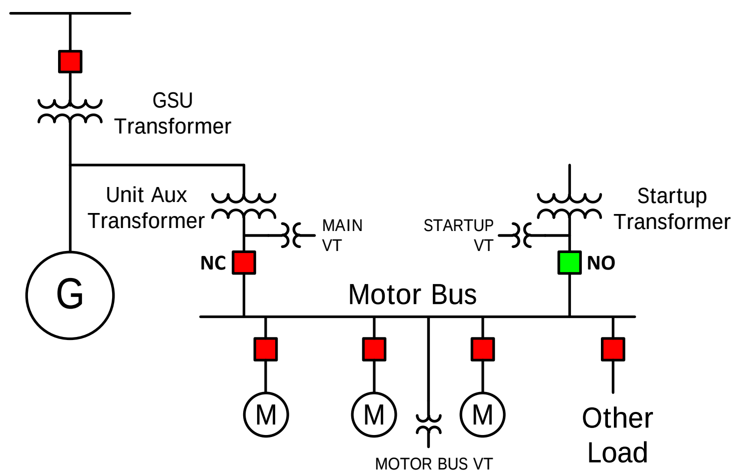


BECKWITH ELECTRIC CO. INC.

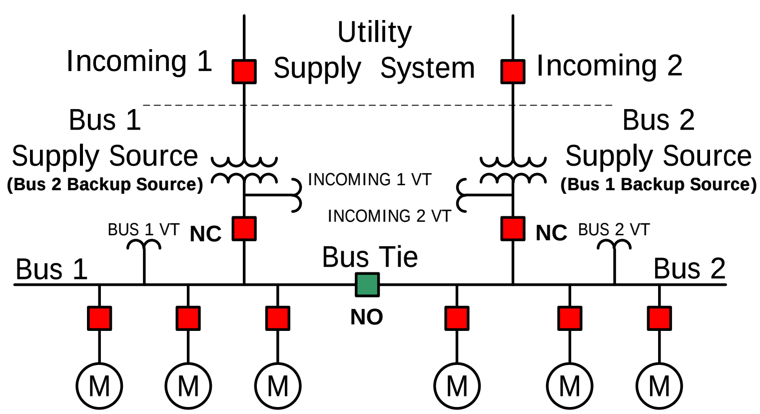
INTRODUCTION

This report explores testing of the M-4272 Motor Bus Transfer (MBT) System by Beckwith Electric.

The M-4272 is a digital MBT System designed to support planned as well as emergency transfers of a motor bus between different electrical supplies. This transfer involves two sources, with either 2 breaker (primary-backup) or with 3 breaker (main-tie-main) arrangements commonly employed as shown in Figure 1.



Generating Plant: 2 Breaker



Industrial Plant: 3 Breaker

Figure 1: Typical Motor Bus Supply Arrangements

Planned transfer methods include either a Hot Parallel (Closed Transition) Transfer, or a Fast with In-Phase (Open Transition) Transfer. The Hot Parallel, Fast, and In-Phase Transfers offer process continuity with a smooth synchronous transfer. Residual voltage and Fixed Time Transfers are never used for planned transfers.

Emergency transfers occur due to internal plant faults, external utility supply faults, plant electrical failures, utility source failure and utility voltage sag. Emergency Transfers only employ Open Transition Transfer Methods and include Fast, In-Phase, Residual Voltage, and Fixed Time Transfers, although Fixed Time Transfers always involve a shutdown of the plant or process. The Fast and In-Phase Transfers offer process continuity with a smooth synchronous transfer. Residual Voltage Transfers typically cause process interruption and restart, as load shedding may be necessary and motors may undergo high restart torques. Properly sequenced motor restart is then required to prevent excessive voltage dip.

Figure 2 shows various transfer zones of Fast (Zone 1), In-Phase (Zone 2) and Residual Voltage (Zone 3) illustrating bus decay characteristics:

- Phase angle difference behavior between the disconnected (decelerating) motor bus and the go-to source
- Disconnected (decelerating) motor bus voltage. Note: The go-to source is assumed to be at 1 per unit voltage

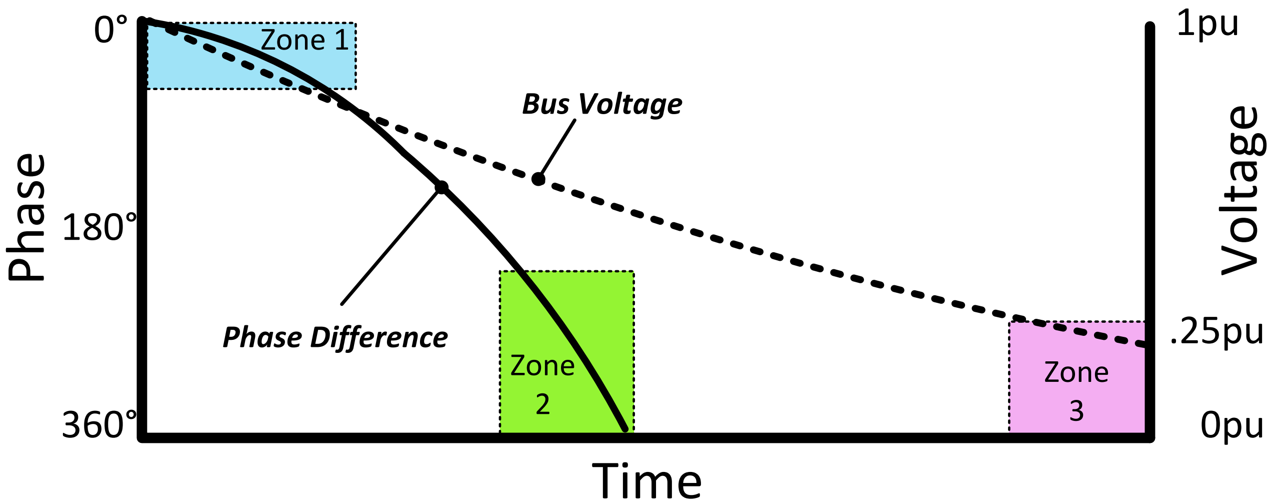


Figure 2: Motor Bus Transfer Zones

The purpose of this testing is to demonstrate the viability of the Fast Transfer and the In-Phase Transfer with various motor bus inertias with associated Hz/sec and V/sec decay rates as described in a report from the IEEE Power System Relaying Committee, "Motor Bus Transfer Applications Issues and Considerations" issued in May 2012. Although Residual Voltage was enabled for the tests, all Transfers were completed successfully by Fast or In-Phase Methods well before the voltage decayed enough to permit a Residual Voltage Transfer.

The test protocol is described hereinafter, and the test results are tabulated. The New Source breaker closing time is fixed, leaving only the variables of the motor bus inertia (frequency and voltage decay rates) and the initial phase angle.

High bus inertia is characterized by a relatively slow rate of frequency change and of voltage change. Low bus inertia is characterized by a relatively rapid rate of frequency change and of voltage change. Bus inertia can change on a given bus due to the types of motors connected to the bus (induction and/or synchronous) and loading characteristics (pumps, positive displacement compressors, fans, conveyors).

Initial phase angle between the motor bus and the New Source can rapidly change just prior to tripping the Old Source Breaker due to system load flow between the old source and new source, transformer configuration induced phase angle differences between the old and new sources, fault angle impressed across the new source, nearby generation power swings on the old source, and voltage depression and recovery from system faults. Just after tripping the Old Source Breaker, an instantaneous phase angle shift occurs from the motors, once they are disconnected from the Old Source.

MBT TEST PROTOCOL

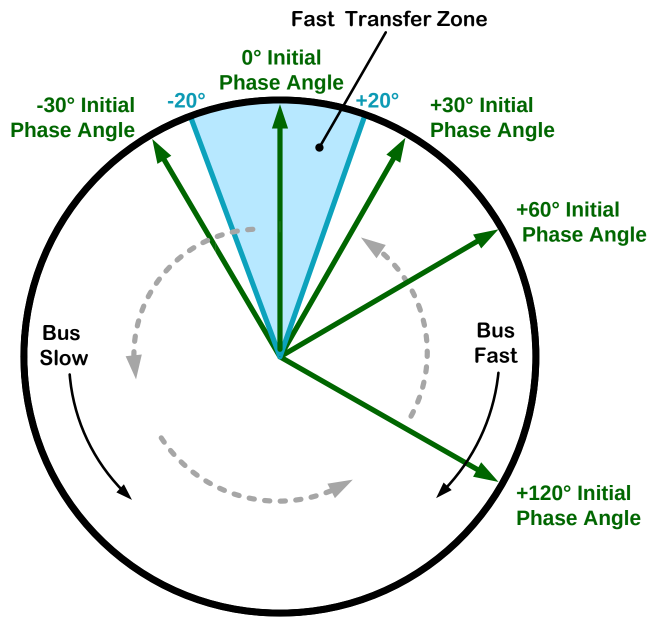
Purpose:
The purpose of the test protocol is to demonstrate the capabilities of a Motor Bus Transfer (MBT) System employing Fast, In-Phase, and Residual Voltage Transfer Methods, under the wide range of motor bus inertias (Hz/sec and V/sec decay rates) encountered in the industry as defined in the IEEE PSRC Report, "Motor Bus Transfer Applications Issues and Considerations".

Equipment:
The Motor Bus Transfer System shall be tested with a circuit breaker simulator consisting of medium voltage vacuum circuit breakers and an Omicron test set. The Omicron Relay Test Set shall employ macros created to provide automated and consistent test conditions. The breaker supplying the motor bus, just prior to transfer, is designated as the "Old Breaker" and the go-to power source to be transferred to, is designated the "New Breaker". Motor Bus Transfer System Software, installed on a laptop, shall be used to download and analyze the captured transfer data.

Methodology:
The Transfers demonstrated shall be 2-Breaker, Protective Relay-Initiated Transfers for a Generating Plant from the Unit Auxiliary Breaker (old breaker) to the Startup Breaker (new breaker). Fast, In-Phase, and Residual Voltage Transfer Methods shall be Enabled concurrently, and all transfers shall be performed in Sequential Mode wherein the auxiliary contact on the Old Breaker confirms the Old Breaker trip before proceeding with the transfer to the New Breaker by one of these Methods.

Equipment Under Test:
Beckwith Electric Co., Inc.
M-4272 Motor Bus Transfer System with M-4272 ISSCom® Software
Settings: Fast Transfer: Maximum Slip Frequency, 2.0 Hz; Maximum Phase Angle, +/- 20°
In-Phase Transfer: Maximum Slip Frequency, 10 Hz
Residual Voltage Transfer: Under Voltage Setpoint: 40 Vac

Transfer Test Conditions:
Transfer Tests shall be performed with initial static Phase Angles of -30°, +120°, +60° +30° and 0° across the New Breaker. Transfers shall then be initiated, opening the Old Breaker, and shall be performed with the resultant Voltage and Frequency Decay representing aggregate High, Medium, and Low Inertia Motors on the Bus, as defined in the IEEE PSRC Report. The Transfer Method and conditions at New Breaker close shall be recorded.



HIGH INERTIA BUS

TEST 1

- Initial Phase Angle across New Breaker: -30 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate High Inertia Motors on the Bus
- Voltage Decay: 75 V/sec
- Frequency Decay: 8.33 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 2

- Initial Phase Angle across New Breaker: +120 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate High Inertia Motors on the Bus
- Voltage Decay: 75 V/sec
- Frequency Decay: 8.33 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 3

- Initial Phase Angle across New Breaker: +60 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate High Inertia Motors on the Bus
- Voltage Decay: 75 V/sec
- Frequency Decay: 8.33 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 4

- Initial Phase Angle across New Breaker: +30 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate High Inertia Motors on the Bus
- Voltage Decay: 75 V/sec
- Frequency Decay: 8.33 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 5

- Initial Phase Angle across New Breaker: 0 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate High Inertia Motors on the Bus
- Voltage Decay: 75 V/sec
- Frequency Decay: 8.33 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

Medium Inertia Bus

TEST 6

- Initial Phase Angle across New Breaker: -30 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate Medium Inertia Motors on the Bus
- Voltage Decay: 94 V/sec
- Frequency Decay: 20 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 7

- Initial Phase Angle across New Breaker: +120 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate Medium Inertia Motors on the Bus
- Voltage Decay: 94 V/sec
- Frequency Decay: 20 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 8

- Initial Phase Angle across New Breaker: +60 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate Medium Inertia Motors on the Bus
- Voltage Decay: 94 V/sec
- Frequency Decay: 20 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 9

- Initial Phase Angle across New Breaker: +30 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate Medium Inertia Motors on the Bus
- Voltage Decay: 94 V/sec
- Frequency Decay: 20 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 10

- Initial Phase Angle across New Breaker: 0 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate Medium Inertia Motors on the Bus
- Voltage Decay: 94 V/sec
- Frequency Decay: 20 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

LOW INERTIA BUS

TEST 11

- Initial Phase Angle across New Breaker: -30 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate Low Inertia Motors on the Bus
- Voltage Decay: 104 V/sec
- Frequency Decay: 31 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 12

- Initial Phase Angle across New Breaker: +120 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate Low Inertia Motors on the Bus
- Voltage Decay: 104 V/sec
- Frequency Decay: 31 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 13

- Initial Phase Angle across New Breaker: +60 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate Low Inertia Motors on the Bus
- Voltage Decay: 104 V/sec
- Frequency Decay: 31 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 14

- Initial Phase Angle across New Breaker: +30 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate Low Inertia Motors on the Bus
- Voltage Decay: 104 V/sec
- Frequency Decay: 31 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

TEST 15

- Initial Phase Angle across New Breaker: 0 degrees
- Initiate Transfer, open Old Breaker, with Voltage and Frequency Decay representing aggregate Low Inertia Motors on the Bus
- Voltage Decay: 104 V/sec
- Frequency Decay: 31 Hz/sec
- Download Oscillography, Transfer Event Log, Sequence of Events, Secondary Metering & Status
- Analyze Results

MBT TEST RESULTS

	TEST	Initial Ø Angle	Voltage Decay	Frequency Decay	Transfer Mode	Transfer Method	Advance Ø Angle	Close Ø Angle	Close ΔF	Close Volts	ANSI C50.41 pu V/Hz	Open Transfer Time cycles
HIGH INERTIA	1	-30	75 V/sec	8.33 Hz/sec	Sequential	IN-PHASE	25.8	0.7	-3.87	85.3	0.24	27.0
	2	+120	75 V/sec	8.33 Hz/sec	Sequential	IN-PHASE	15.5	-0.1	-2.24	99.9	0.14	15.2
	3	+60	75 V/sec	8.33 Hz/sec	Sequential	FAST	16.5	7.0	-1.46	106.9	0.15	9.8
	4	+30	75 V/sec	8.33 Hz/sec	Sequential	FAST	19.3	12.6	-0.70	112.3	0.22	5.0
	5	0	75 V/sec	8.33 Hz/sec	Sequential	FAST	-1.3	-4.0	-0.27	116.6	0.08	1.7
MEDIUM INERTIA	6	-30	94 V/sec	20 Hz/sec	Sequential	IN-PHASE	40.7	1.7	-5.76	93.3	0.15	16.7
	7	+120	94 V/sec	20 Hz/sec	Sequential	IN-PHASE	28.1	6.5	-3.24	105.0	0.09	9.5
	8	+60	94 V/sec	20 Hz/sec	Sequential	IN-PHASE	18.9	-1.7	-2.19	108.3	0.07	6.2
	9	+30	94 V/sec	20 Hz/sec	Sequential	FAST	18.3	5.7	-1.21	112.8	0.09	3.5
	10	0	94 V/sec	20 Hz/sec	Sequential	FAST	-4.6	-10.9	-0.68	116.3	0.20	1.8
LOW INERTIA	11	-30	104 V/sec	31 Hz/sec	Sequential	IN-PHASE	59.5	11.9	-6.96	97.1	0.15	13.3
	12	+120	104 V/sec	31 Hz/sec	Sequential	IN-PHASE	30.4	2.9	-3.79	105.7	0.06	7.3
	13	+60	104 V/sec	31 Hz/sec	Sequential	IN-PHASE	22.1	-2.1	-2.86	110.6	0.07	5.0
	14	+30	104 V/sec	31 Hz/sec	Sequential	FAST	17.8	1.7	-1.56	113.2	0.04	2.8
	15	0	104 V/sec	31 Hz/sec	Sequential	FAST	-5.7	-13.4	-0.84	115.5	0.26	1.5

SUMMARY AND CONCLUSIONS

1. Applying this MBT Test Protocol to the M-4272 Motor Bus Transfer System, the M-4272 transferred High, Medium, and Low Inertia motor buses, with multiple initial angles, with ALL closing under 0.26 pu V/Hz. All tests were performed without any changes to settings. The Fast Transfer Method was set with the Phase Angle Limit at 20° and the Slip Frequency Limit at 2.0 Hz. The In-Phase Transfer Method was set with the Slip Frequency Limit at 10.0 Hz.

2. The 2 Hz limit can be seen coming into play in Tests 2, and 8 as the In-Phase Transfer Method takes over from the Fast Transfer Method, and actually sends the close command inside the 20° limit. The Fast Transfer was blocked just before the phase angle entered its 20° operate window, as its 2 Hz Slip Frequency Limit was exceeded just before the phase angle entered the window. Closes were then performed by the In-Phase Method at 0.14 and 0.07 pu V/Hz respectively.

   The effect of the 2 Hz Slip Frequency Limit used to block to Fast Transfer is calculated with the equation:

   $$\Delta Ø=360(S_{INIT}+R_{S}T_{BC})T_{BC}$$

   Given a Breaker Close Time (T_{BC}) of 1.5 cycles or 25ms, a 2 Hz initial slip frequency at breaker close initiate (S_{INIT}), and the rate of increase in slip frequency (R_S) while the breaker is closing, the phase angle can change 20° to 25° during the breaker close. If the initial angle across the new source breaker is outside the Phase Angle Limit prior to initiating a transfer, and therefore may rapidly be approaching the Fast Transfer operate window, the Slip Frequency Limit can be used to coordinate the actions of the Fast Transfer and the In-Phase Transfer Methods to achieve an optimal close and also to prevent the new breaker close from occurring at excessive angles.

3. For years, ANSI C50.41 Polyphase Induction Motors for Power Generating Stations has stated:

   A fast transfer or reclosing is defined as one which:

   a) occurs within a time period of 10 cycles or less,

   b) the maximum phase angle between the motor residual volts per hertz vector and the system equivalent volts per hertz vector does not exceed 90 degrees, and

   c) the resultant volts per hertz between the motor residual volts per hertz phasor and the incoming source volts per hertz phasor at the instant of transfer or reclosing is completed does not exceed 1.33 per unit volts per Hz on the motor rated voltage and frequency basis.

4. The MBT Test Results fully comply with b) and c) above from ANSI C50.41. The attached MBT Test Results of 0.26 pu V/Hz or less are well below the 1.33 pu V/Hz and 90 degree limits.

5. However, as the selected test results below show for the whole range of possible motor buses with different inertia, the "10 cycles or less" criteria must not be applied to the In-Phase Transfer Method, as it just may take more than 10 cycles for the motors to rotate back into synchronism and experience a perfectly good transfer.

   - A High Inertia close at 0.24 pu V/Hz took 27 cycles.
   - A Medium Inertia close at 0.15 pu V/Hz took 16.7 cycles.
   - A Low Inertia close at 0.15 pu V/Hz took 13.3 cycles.

6. Therefore, the old arbitrary 10-cycle limit must be ignored or risk blocking a perfectly good close. How fast can the motors transfer? When the motors allow it by rotating back into sync! With the In-Phase Transfer Method now added as a second synchronous method of "Fast" Transfer per the definition of C50.41, this 10-cycle restriction can be eliminated.

7. Moreover, in the fast-moving world of motor bus transfer, 10 cycles (167ms) is an eternity and never was a safe limit for Fast Transfer. Even at the High Inertia frequency decay of 8.33 Hz/sec, the angle movement in 10 cycles is a dangerous 84°.

8. All transfers were completed using the Sequential Transfer Mode where “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.” This inherent breaker failure scheme adds a little time to the transfer, still yielding excellent transfer results, but avoids the possibly catastrophic result where the two breakers are closed at the same time. The Simultaneous Transfer Mode initiates transfer of both trip and close breaker operations simultaneously, and thereby does not prevent the new breaker from closing if the old breaker fails to trip.

9. It is clear from the bus voltage levels at the point of completion of the transfer that the synchronous Fast and In-Phase Transfers always occur well before the Residual Voltage Slow Transfer would operate. The voltage never gets down to the 0.3pu voltage level of 40V that would initiate a Residual Voltage Transfer. These synchronous transfers always occur at much higher voltages, at much lower slip frequencies, and coupled with the synchronous closure, provide a far gentler transfer than the “blind” Residual Voltage Method.

10. Due to the high-speed performance of the Fast and In-Phase Methods, even under Low Inertia conditions, these Methods can be applied not only to Medium Voltage Motor Buses, but also to Low Voltage (480- and 600-Volt) Motor Buses, rather than having to resort to Residual Voltage Slow Transfer.

11. The In-Phase Transfer Method of the M-4272 Motor Bus Transfer System offers the opportunity to effect successful transfers while the motors are still spinning at a relatively low slip frequency (high RPM), allowing them to quickly reaccelerate to rated speed. Successful transfers were made with low resultant per unit V/Hz, as all the test results demonstrate. With the In-Phase Method, the lower resultant V/Hz is due to the M-4272 patented df/dt algorithm and its ability to accurately predict a zero phase angle closure of the new source breaker.

12. The M-4272 Motor Bus Transfer System measuring elements are ultra-high speed and extremely accurate in order to properly execute in highly dynamic system conditions encountered just prior to and during bus transfer, with rapidly changing voltage, frequency, and phase angle. With all IEEE-recognized Open Transition Transfer Methods enabled, the M-4272 will automatically select the optimal method, providing the greatest opportunity for process continuity, as the motors are still spinning with sufficient flux for low reacceleration current and associated low torque.

13. Residual Voltage Transfers provide the least opportunity for process continuity, as the motors on the bus will have coasted down significantly in speed, possibly coupled with the jarring effect of a large phase angle at breaker closure. Thereby the motors are subject to large reacceleration current and associated torque.

ANNEX "A": 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 (Hot 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. Fast, in-phase, residual and fixed time transfers are open transition transfers.
- **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.
- **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. It utilizes a high speed specialized synchronizing relay that is accurate and fast enough to calculate slip frequency as well as deceleration of the motor bus in order to predict, considering the new source breaker closing time, the new source breaker closes at phase coincidence (0°) between the motor bus and the new source.
- **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 voltage 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.
- **Fixed Time 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, typically >=60 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.
- **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.
- **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.

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