MOTOR BUS TRANSFER SYSTEM PERFORMANCE TESTING AND THE SEARCH FOR A NEW TRANSFER SUCCESS CRITERION

Thomas R. Beckwith
Life Member, IEEE
Beckwith Electric
TBeckwith@BeckwithElectric.com

Dr. Murty V.V.S. Yalla
IEEE Fellow
Beckwith Electric
MYalla@BeckwithElectric.com

Abstract – The electric power industry presently has no industry standards on the performance requirements for relays used to supervise power plant auxiliary motor bus transfers. A device testing protocol is proposed for relays used to implement the fast and in-phase methods of motor bus synchronous transfer, and the results of this extensive performance testing are analyzed. The existing industry criteria for determining the success of a completed transfer are used to evaluate these test results. Dynamic conditions that occur during bus transfer are discussed, linking their relevance to this performance testing. The development of digital motor bus transfer systems, capable of simultaneously recording three-phase transfer data from both sources and the motor bus, provides key insight into what happens during actual transfers. Case studies of a number of live motor bus transfers at power generation facilities are presented and analyzed to derive a new transfer metric, based on the ratio of the aggregate peak torque after the transfer to the aggregate load torque prior to the transfer. This metric is compared with the existing industry criterion at the instant of transfer, and correlation between the two metrics is investigated.

I. INTRODUCTION

To maintain continuity of power plant auxiliary loads for loss of supply, motor buses require transfer from an existing source to a new source. In an Open Transition Transfer, the existing source breaker is tripped before the new source breaker is closed. Thus, there is a period of time when the motor bus is not connected to either source. There are two basic bus structures under which motor bus transfer is applied within power plants: Main-Tie-Main and Primary-Backup. A combined-cycle power plant may employ a Main-Tie-Main configuration, where two separately-sourced motor buses are connected by a normally open tie breaker. In the case of a generator startup, shutdown, or an emergency trip of a generator, the transfer is achieved by tripping that generator source breaker and moving its load to the other generator source by closing the tie breaker. The two motor buses are now sharing the good source. In the Primary-Backup configuration, a single motor bus is directly transferred between two sources, and is employed in power plant auxiliary applications where emergency tripping of a generator may require transfer of the auxiliary plant load to a dedicated alternate supply. A Primary-Backup transfer may also be initiated during a planned generator startup or shutdown.

For years, the electric power industry has depended on power plant auxiliary motor bus transfer techniques employing devices with no industry standards on the performance requirements of devices supervising this application. The costly consequences of a failure to transfer or hard transfers with cumulative damage to motors and motor loads are no longer acceptable. And the only criteria for determining the success of a completed transfer is the ANSI C50.41-2012 limit of 1.33 per unit Volts per Hertz [1], a value which is rarely ever calculated to judge compliance of the transfer system during actual planned or emergency transfers. Failure to verify compliance under all possible conditions could ultimately lead to loss of power plant auxiliary loads or catastrophic damage.

Published in May 2012, the IEEE Power System Relaying Committee (IEEE PSRC) Report, "Motor Bus Transfer Applications Issues and Considerations" [2], defines In-Phase transfer as, "The 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." The report adds that, with the Fast transfer method, "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." The Fast method sends a breaker close command when the angle between the motors and the new source is within a phase angle limit. The In-Phase method sends a breaker close command at an advance angle before zero degrees to compensate for the breaker close time so that the motors are connected to the new source at zero degrees. Both methods may also be supervised by a frequency difference (slip frequency) limit. The Residual Voltage Transfer method is not a synchronous method as it only closes at low bus voltage and ignores the motor bus to new source phase angle and slip frequency. These are three independent methods that may be concurrently employed in Open Transition Transfers which the IEEE PSRC Report defines as "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."

The first-ever transfer device testing protocol, defining bus frequency and voltage ramp-down conditions for High, Medium, and Low Inertia motor buses, was published in the IEEE report. The relevance of this new protocol will be discussed with regard to application of the test results to the approval or rejection of devices considered for supervision of transfers. This paper then presents an expanded device testing protocol, and the results of extensive performance testing of devices identified to implement the Fast and In-Phase methods of motor bus synchronous transfer described in the IEEE report. Dynamic conditions that occur immediately prior to and during bus transfer are discussed, linking their relevance to this performance testing. Case studies of several live motor bus transfers at power generation facilities are then used to derive new transfer metrics, based on transfer inrush current and power when transfer is completed. These metrics are correlated with the calculated per unit Volts per Hertz at the instant transfer is completed. The effects on these metrics of the Fast, In-Phase, and Residual Voltage methods of transfer and the subsequently-defined Sequential vs. Simultaneous mode of transfer will be investigated.

II. BACKGROUND - IEEE PSRC HIGH-SPEED SYNC-CHECK PERFORMANCE TEST

A Motor Bus Transfer report that was published in 1993 by the IEEE PSRC [3] 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.” However, this report did not attempt to quantify what is meant by “high-speed sync-check.”

For the purpose of developing a standardized testing protocol for sync-check relays employed to supervise a Fast Transfer, the May 2012 IEEE PSRC report sought to expose the unit under test to a wide range of application conditions. The purpose was to test the response characteristics of the sync-check phase angle detection with zero or no intentional time delay response to phase movements into and out of the operate phase angle limit. Thus, the relay was subjected to a wide range of combined frequency and voltage decay times moving through its pickup and dropout point. Three combinations of decay times were selected, representing High, Medium, and Low Inertia of the aggregate motors upon disconnect from the bus. With a phase angle limit set value of 20°, the actual measured pickup and dropout values were noted. The motor bus transfer (MBT) device testing protocol published in the IEEE report allows the user to determine whether the supervising sync check relay operates fast enough to prevent the loss of the motor bus or to prevent catastrophic damage due to an out-of-sync close. The user is left to determine whether the response time error was acceptable for use in a Fast motor bus transfer scheme.

III. FAST AND IN-PHASE METHODS - DEVICE PERFORMANCE EXPANDED TESTING

Expanding on this concept, a standardized device testing protocol will now be developed, using the same IEEE PSRC published ramp-down conditions for the performance testing of devices identified to implement the Fast and In-Phase methods of motor bus synchronous transfer as defined in the IEEE PSRC report.

Based on industry experience, given the relatively linear nature of the open transition frequency and voltage decay over time, this linear ramp-down test protocol was considered to allow standardized testing representing a wide range of high to low inertia motor buses. This way, results could be compared, using the per unit V/Hz criteria from ANSI C50.41, and allow the industry to make its own conclusions as to the applicability of devices being considered for the purpose of supervising motor bus transfer.

Before proceeding with a detailed description of this new test protocol, it is necessary to review conditions or phenomena that were identified in the IEEE PSRC report that exist or occur before the initial source breaker is tripped and indeed may have precipitated disconnecting from the initial source in anticipation of transferring to the alternate source. As the report states, “These conditions or events affect the phase angle and frequency difference across the open alternate source breaker or the voltage of the alternate source.” The report identifies the following that affect the transfer initial angle and slip frequency:

- The effects of a fault on the initial source and factors such as type and proximity of the fault causing a dynamic change in the phase angle across the alternate breaker.
- Variation of the generator internal rotor angle leading to an Out-of-Step (OOS) generator trip appears as an increase in phase angle across the alternate breaker. If the unit breaker trips before the unit auxiliary breaker, that phase angle then rapidly changes.
- Incoming supply sources to a facility can come from different parts of the power system at different voltages. This can result in substantial fluctuating phase angle difference between the two sources and thus across the alternate breaker. Abnormal system operation can increase the system separation or even cause the systems to break apart. In such cases, the phase angle across the alternate breaker could be any value and could even be rotating.

- At some facilities, supply source transformers are installed where the effect of the primary to secondary winding phase shift creates a permanent standing angle across the alternate source breaker.

Once transfer is initiated, and after tripping the initial source breaker, another phenomena occurs, characteristic of induction motors, and that is the essentially instantaneous phase shift upon source disconnect, followed by the bus frequency decay.

One must add an additional effect to those identified in the report, and that is the effect of the depressed voltage while the fault is present. As an example, consider the source structure in Fig. 1 at a power plant where a fault occurs as shown on the 230 kV ring bus. Until the fault is cleared, it will depress the voltage across the 230 kV bus. The generator unit breaker and 230 kV bus breakers are tripped, and focusing attention on the motor bus at the bottom of the one-line, and based on the position of this fault, the unit auxiliary transformer NC breaker will also trip, disconnecting the motor bus. However, due to the depressed voltage, completion of the transfer must wait until the startup transformer is isolated from the fault. Once isolated, the startup source voltage recovers, and the transfer can continue as the phase angle across the alternate breaker rotates towards the next synchronous pass through zero degrees. See Fig. 2.

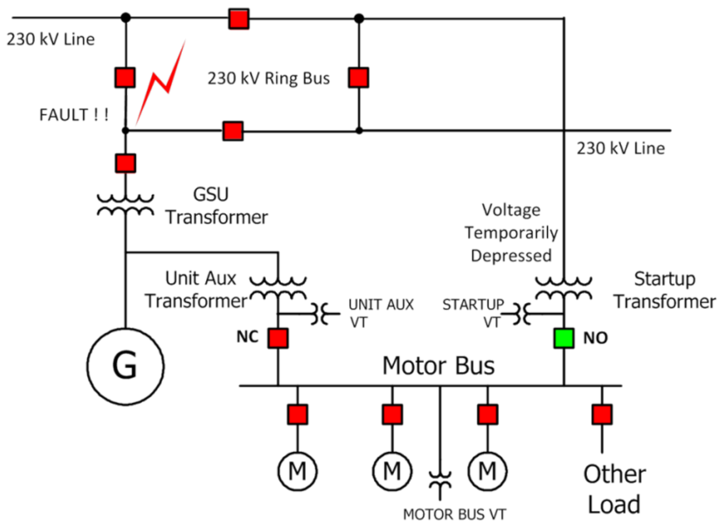

Fig. 1 Power Plant 230 kV Ring Bus Fault

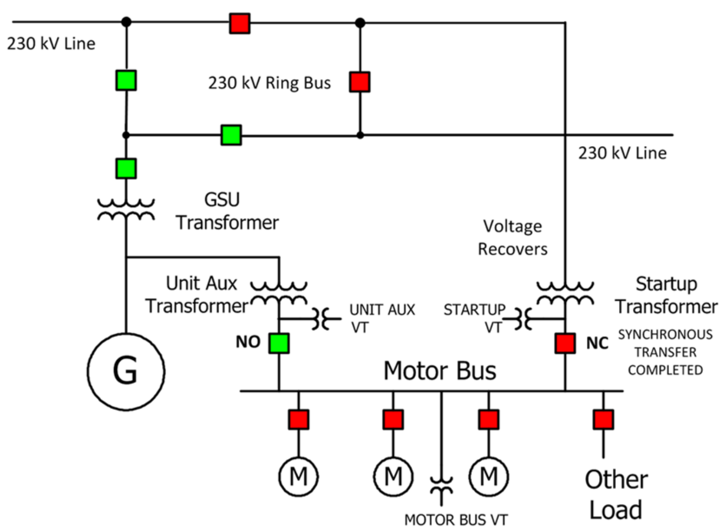

Fig. 2 Power Plant Motor Bus Transfer Completed

An Open Transition Transfer, that disconnects the motors prior to closing the alternate source, allows the motors to spin free and rotate back through synchronism where the alternate source breaker can be closed. However, the previously mentioned conditions or phenomena suggest that the new test protocol should include a variety of initial start angles at each level of motor bus inertia applied. Furthermore, ANSI C50.41-2012 clause 14.3 states, “test conditions should account for any phase angle difference between the incoming and running power supplies.”

IV. DEVICE PERFORMANCE EXPANDED TEST SETUP

The equipment under test (EUT) was connected to operate two medium voltage circuit breakers. The initially closed breaker is designated as the “Old Breaker” and the initially open breaker that will be closed into the new source at the point of transfer completion is designated the “New Breaker.” The commands to operate and the auxiliary contacts indicating operation of these breakers were monitored. A protective relay test set employed macros created to provide automated and consistent test conditions, replicating a wide range of motor sizes and loads. The injected voltage and frequency decay rates, identified in Table I, represent the aggregate spindown characteristics of the motors on the bus after the Old Breaker is tripped. These decay rates, defined in the 2012 IEEE PSRC report, cover the range from large medium voltage motors with high inertia loads to smaller low voltage motors with lower inertia loads. As the injected frequency decays, this represents the slowdown of the motors relative to the new source as the resultant negative frequency difference or slip frequency increases. Software of the device under test, installed on a laptop, was used to download and analyze the captured transfer data and oscillography.

V. SETTINGS – EQUIPMENT UNDER TEST

- Fast Transfer: Phase Angle Limit, +/- 20°; Slip Frequency Limit, 2.0 Hz
- In-Phase Transfer: Slip Frequency Limit, 10 Hz; Phase Angle automatically calculated for Breaker Close near 0° ± Breaker Close Time Error
- Breaker Close Time: 1.2 cycles
- Residual Voltage Transfer: Residual Voltage setpoint, 40 Vac on a 120 Vac PT secondary
- The Fast, In-Phase, and Residual Voltage Transfer methods were all enabled concurrently.
- All transfers were set to operate in Sequential Transfer mode wherein the auxiliary contact on the Old Breaker confirms the Old Breaker trip before initiating the transfer to the New Breaker by one of the three methods mentioned previously. This mode was chosen over the Simultaneous mode which has no provision for ensuring the Old Breaker has tripped as it simultaneously initiates both the trip of the Old Breaker and the supervised close of the New Breaker.

VI. MOTOR BUS TRANSFER TEST CONDITIONS

In consideration of the phenomena that may exist or occur before the initial source breaker is tripped, transfer tests were performed as shown in Fig. 3 with initial static phase angles of -30°, +120°, +60°, +30° and 0° across the New Breaker. The -30° angle was chosen as the worst case since this was initially outside the IEEE PSRC report phase angle limit set value of 20°. Thus, the motor bus would have to rotate 330° to pass through 0°. The other values were chosen to investigate the coordination of the three transfer methods as the phase angle approaches 0°. Transfers were then protective relay-initiated, tripping the Old Breaker, and initiating the frequency and voltage decay. Tests were first performed under the High Inertia, slower decay rates at all initial angles, and then repeated at the faster decay rates representative of Medium Inertia, and Low Inertia motor buses, as defined in the IEEE PSRC report. The transfer method, mode, breaker command advance phase angle, and the phase angle, frequency difference (ΔF), and bus voltage values at the instant of New Breaker close were recorded.

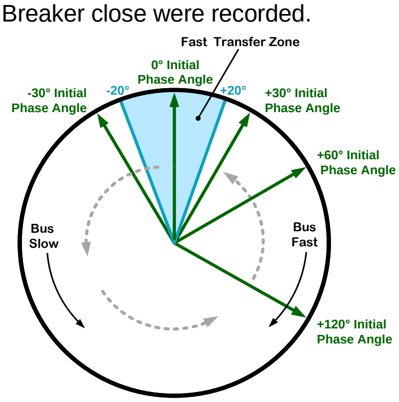

Fig. 3 Transfer Test Initial Static Phase Angles

VII. MOTOR BUS TRANSFER TEST RESULTS

Applying this MBT test protocol to the transfer system, the EUT transferred High, Medium, and Low Inertia motor buses, starting from multiple initial angles, and in all cases closing under 0.26 pu V/Hz. All tests were performed without any changes to settings. See Table I. [4]

TABLE I

MBT Test 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

VIII. MOTOR BUS TRANSFER TEST CONCLUSIONS [4]

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.

The influence of the Fast Transfer 2 Hz Slip Frequency Limit can be seen 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.

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

$$\Delta Ø = 360(S_{INIT}+0.5R_S T_{BC})T_{BC}$$

Given a breaker close time (T_{BC}) of 1.5 cycles or 25ms, and a 2 Hz initial slip frequency (S_{INIT}) at the breaker close command, we use the formula previously stated to calculate the phase angle movement ($\Delta Ø$) at the High and then at the Low Inertia rate of frequency decay (R_S) while the breaker is closing. During a breaker close at the High Inertia rate of 8.33 Hz/sec, the phase angle can move 18.9°, and at the Low Inertia rate of 31 Hz/sec, the phase angle can move 21.5°. 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 during transfer, the Fast Transfer Slip Frequency Limit blocking action can be used to coordinate the actions of the Fast Transfer and the In-Phase Transfer methods. This achieves an optimal close with the In-Phase Transfer method and prevents the new breaker close from occurring at excessive angles.

For years, ANSI C50.41 Polyphase Induction Motors for Power Generating Stations [1] 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.

A review of these test results yields the following observations with regard to the requirements of ANSI C50.41 and to electric power industry bus transfer practices in general:

1. The test results fully comply with b) and c), previously stated, from ANSI C50.41. The Table I MBT Test Results of 0.26 pu V/Hz or less are well below the 1.33 pu V/Hz and 90 degree limits.
2. However, as the following selected test results 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 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.

   Therefore, the old arbitrary 10-cycle limit must be ignored or risk blocking a perfectly good transfer. 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.
3. Moreover, in the fast-moving world of motor bus transfer, 10 cycles (167ms) is an eternity and never was a safe limit for the C50.41 fast transfer. Even at the Medium Inertia frequency decay of 20 Hz/sec (R_S), with zero initial slip frequency (S_{INIT}), the angle movement ($\Delta Ø$) in 10 cycles (T), per the equation $\Delta Ø = 360(S_{INIT}+0.5R_S T)T$, is a dangerous 100°.
4. All transfers were completed using the Sequential Transfer mode, defined as when “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.” [2] 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 both the trip and the close breaker operations simultaneously and thereby does not prevent the new breaker from closing if the old breaker fails to trip. Except in cases of extremely low inertia, the need for speed could become a vestige of the past as, with modern technology, we now have the luxury to wait for the old breaker to trip.
5. The In-Phase Transfer method of the 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.
6. 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 0.33 pu voltage level of 40 Vac that would transfer on Residual Voltage. 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.
7. Residual Voltage Transfers provide the least opportunity for maintaining continuity of power plant auxiliary loads, 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.

8. 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 slow Residual Voltage Transfers.

IX. MOTOR BUS TRANSFER FIELD RESULTS

Oscillographs were collected from a number of on-site commissioning events representing live Open Transition Transfers under normal operating load conditions. The results of the analysis of the oscillographs are tabulated in Table II.

TABLE II
MBT Field Results

MBT FIELD RESULTS VS = 120 FS = 60

LOCATION	Transfer Mode	Transfer Method	Advance Ø Angle	Close Ø Angle	Close ΔF	Close Volts	ANSI C50.41 pu V/Hz	Open Transfer Time cycles	Max Transfer Amps / FLA	Max Transfer pu Power	Torque Ratio T_{PK}/T_L
FACILITY 1	Simultaneous	FAST	-0.1	-20.0	-2.83	93.8	0.3622	1.3	4.6	21.5	4.12
FACILITY 2	Sequential	FAST	-10.8	-16.3	-0.19	100.4	0.3054	5.0	2.4	5.9	2.38
FACILITY 3	Simultaneous	FAST	-3.0	-18.5	-0.81	103.4	0.3260	3.3	3.1	9.3	2.48
FACILITY 4	Sequential	FAST	-0.8	-6.8	-0.23	107.9	0.1489	2.9	2.7	7.2	1.97
FACILITY 5	Simultaneous	FAST	-1.2	-12.6	-1.76	103.2	0.2360	1.3	2.2	4.9	1.87
FACILITY 6	Simultaneous	FAST	-1.1	-16.5	-2.25	102.0	0.2939	1.4	1.8	3.3	1.62
FACILITY 7	Sequential	FAST	-2.8	-17.1	-0.49	98.7	0.3201	2.9	2.9	8.4	2.08
FACILITY 8	Sequential	FAST	-2.2	-12.7	-0.38	99.0	0.2635	2.9	1.8	3.3	1.50
FACILITY 9	Sequential	Residual Voltage	152.4	128.4	-1.66	34.7	1.2074	48.7	4.8	23.0	21.74
FACILITY 10	Sequential	IN-PHASE $Ø_{INIT}$ =115°	55.0	-7.7	-2.77	44.4	0.6178	9.4	2.4	6.0	2.39
FACILITY 11	Sequential	IN-PHASE	78.9	7.1	-4.48	37.7	0.6644	17.7	2.3	5.2	1.89
FACILITY 12	Simultaneous	FAST	-0.1	-20.3	-2.23	89.4	0.3838	1.7	1.8	3.4	1.79

X. MOTOR BUS TRANSFER FIELD OBSERVATIONS AND CONCLUSIONS

Although the Fast and In-Phase (Synchronous) Transfer methods were both enabled, the results showed that Fast Transfers occurred in nine events, and In-Phase Transfers occurred in two events. All of the Synchronous Transfer breaker close commands occurred at voltages above which the Residual Voltage Transfer undervoltage element would have operated. The one Residual Voltage Transfer event occurred when the Synchronous Transfer methods were purposely disabled, so the results for a Residual Voltage Transfer could be observed.

All of the Synchronous Transfers were completed at between 0.15 and 0.66 pu V/Hz, all well under the ANSI C50.41 limit of 1.33 pu V/Hz, and the one Residual Voltage Transfer closed at 1.21 pu V/Hz.

It is interesting to note that the FACILITY 11 In-Phase Transfer closed at about the same voltage as the FACILITY 9 Residual Voltage Transfer, with the results in Table III.

TABLE III
In-Phase vs. Residual Voltage Results

FACILITY 11 In-Phase	FACILITY 9 Residual Voltage
37.7 Vac	34.7 Vac
-4.48 Hz	-1.66 Hz
7.1°	128.4°
0.6644 pu V/Hz	1.2074 pu V/Hz

The FACILITY 11 In-Phase Transfer occurred at 2.7 times the slip frequency, but with a close angle of 7.1°, versus the Residual Voltage Transfer "blind" close angle of 128.4°, the In-Phase Transfer performed at about half the pu V/Hz.

Although the Open Transfer Times cannot be compared between these events due to variations in aggregate motor size and loads, the ANSI C50.41 definition that a fast transfer occurs within a time period of 10 cycles or less would be violated by the FACILITY 11 In-Phase Transfer that takes 17.7 cycles as the motors rotate back into phase for a successful synchronous close.

It is also noteworthy that at FACILITY 10, the initial phase angle between the motor bus and the new source, $Ø_{INIT}$, prior to tripping the Old Breaker, was 115°. Thus the new source was well out of synchronism with the old source, preventing any immediate attempt to perform a Fast Transfer. The value of the In-Phase method of transfer is clearly demonstrated, providing a synchronous transfer opportunity and completing a successful transfer at 0.6178 pu V/Hz. The breaker close command was sent at an Advance Ø Angle of 55° before zero, and at a bus voltage well above the Residual Voltage Transfer setpoint.

Comparing the results of the Simultaneous Transfer mode with the Sequential Transfer mode, that ensures the old breaker has opened, reveals anticipated observations. The Simultaneous mode Fast Transfers result in expected shorter Open Transfer Times, but this mode is used to ensure transfer in cases of very low motor bus inertia. Note the case at FACILITY 1 where, during the Open Transfer Time of 1.3 cycles, the phase angle moved 19.9°, the slip increased by 2.83 Hz, and the voltage dropped to 93.8 volts, yielding a value of 0.36 pu V/Hz. This is definitely a case where Simultaneous Fast Transfer is required; keeping in mind that a breaker failure scheme is mandatory for the Simultaneous mode of transfer in case the old breaker fails to trip.

ANSI 50.41 refers to motor bus transfer or reclosing transient currents and torques as a multiple of rated values. It is common to see requirements that motor starting current should not exceed a specified multiple of full load current at rated voltage for across-the-line full voltage starting. A ratio was calculated by taking the peak inrush current at transfer, Max Transfer Amps (MTA), and dividing it by the subsequent steady state Full Load Amps (FLA). This was then graphed versus pu V/Hz in Fig. 4 to see if one could observe any correlation that as the pu V/Hz rises, then the Max Transfer Amps/FLA would also rise.

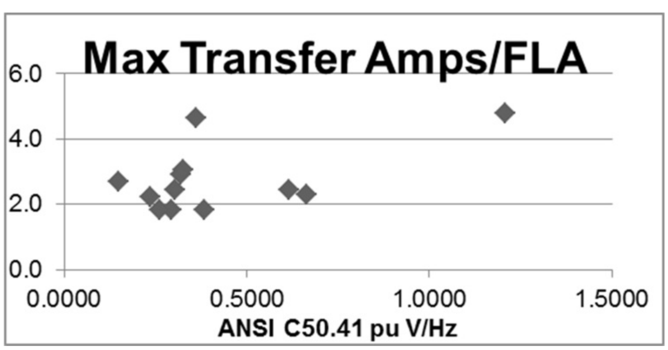

Fig. 4 MTA/FLA vs. pu V/Hz

Clearly there is no such correlation, but it is encouraging that the range of MTA/FLA from 1.8 to 4.8 is reasonable compared to a normal motor start. Since the actual steady state load current may be less than nameplate rated FLA, the ratio of MTA to FLA is possibly overstated in the logged ratios. The actual MTA to nameplate rated FLA could actually even be less than the values logged in Table II. It is also interesting to note that the two In-Phase Transfers, with higher pu V/Hz (0.62 and 0.66 pu V/Hz) than the Fast Transfers, were both in the middle of the range of MTA/FLA (2.4 and 2.3) compared to the Fast Transfers.

The next column introduces a metric where the MTA/FLA of the previous column is squared to get a measure of the Max Transfer pu Power, assuming that the slip frequency, and thereby FLA rotor impedance (Rotor Ω FLA), has not changed significantly during the Open Transfer Time [5].

Since $W = I^2R$, then if we express

$W_{FLA} = (1)^2 1 = 1$ pu Power at Full Load Amps, then

$W_{MTA} = (MTA/FLA)^2 1 =$ Max Transfer pu Power.

Now Locked Rotor Amps (LRA) at 1.0 PU voltage is approximately related to FLA as follows:

LRA = 6 * FLA [5],

and the rotor impedance (Rotor Ω LRA) at LRA vs. FLA is approximately:

Rotor Ω LRA = 3 * Rotor Ω FLA [5], so

$W_{LRA} = (6)^2 3 = 108$ pu Power at Locked Rotor Amps.

Since the ratio of MTA to FLA is possibly overstated, and the Max Transfer pu Power metric uses the current amplitude squared, the real component of the current which produces torque on motors and loads would yield a lesser value of per unit transfer power. In spite of this, the per unit power values calculated on the MBT Field Results are still far below locked rotor per unit power. Future investigation of the transfer inrush voltage and current sign waves in the time domain, treating the aggregate motor bus as a single motor could be used to calculate the torque on such an individual motor. It is possible that this could be considered as another way to evaluate the success of a transfer from values available for the overall transfer.

We realize that the pu V/Hz calculation depends on only three values at closure compared to the new source: the bus voltage difference, the bus frequency difference, and the phase angle difference. One could imagine two vastly different sets of motors with two vastly different sets of loads, but transferring with the same three values at closure. The calculated pu V/Hz would be exactly the same, but one wonders if the motors and loads think so. Therefore, the use of the 1.33 pu V/Hz limit across the open breaker as a criteria for the safe transfer of motor buses leaves room for possible improvement.

XI. A PROPOSED NEW METRIC FOR ASSESSING MOTOR BUS TRANSFERS

The previously mentioned FACILITY 1 through 12 oscillographic records of live motor bus transfers will now be analyzed to derive a new transfer metric, based on the voltage and current during inrush at the close of the new source breaker. These values will be measured in the time domain and employed to calculate the resultant torque as if the aggregate bus were a single induction motor drawing the same current and power. It is inconceivable that a voting scheme of the individual motor torques could realistically be used to permit or deny a transfer of the aggregate bus, but this aggregate bus value could be used as a proxy measure of the severity of the torques on the individual motors.

Torque calculation from the collected field oscillographic data is carried out assuming a single induction motor representing all the motors on a bus. Also, copper losses, iron losses, friction and windage losses are neglected. The torque produced is equal to the electromagnetic power transferred through the air gap ($\mathbf{P_{AG}}$) divided by the synchronous speed ($\boldsymbol{\omega_S}$):

$$\mathbf{T = P_{AG}/\boldsymbol{\omega}_S}$$

The power transferred through the air gap is calculated using time domain samples of the applied voltage and current waveforms from the recorded oscillographs of the actual field events. The load torque prior to the transfer ($\mathbf{T_L}$) was calculated using current signal taken from the existing source along with motor bus voltage signal (digitized samples). The peak torque ($\mathbf{T_{PK}}$) after the transfer has taken place is also calculated using the current signal taken from the new source along with motor bus voltage signal. Then the ratio of $\mathbf{T_{PK}}$ to $\mathbf{T_L}$ is calculated and it is tabulated for each facility in Table IV.

As can be seen from Tables II and IV, the In-Phase Transfer cases (Facilities 10 and 11) have higher pu V/Hz, but did not have higher inrush current (Max Transfer Amps/FLA) or Torque Ratios ($\mathbf{T_{PK}/T_L}$). In fact, the Torque Ratios for the two In-Phase Transfers fall right in the middle of the Torque Ratios for all the Fast Transfers. This indicates the higher pu V/Hz in these two cases is a result of voltage magnitude difference rather than phase angle difference. The real power exchange (which is responsible for the motor torque) between the source and the connected motor during reclosing transients is more related to the phase angle difference rather than the voltage difference. The Torque Ratio (**T_{PK}/T_L**) and pu V/Hz is plotted on a scatter chart shown in Fig 5 for each of the Facilities from 1 to 12 (corresponding Facility numbers are shown next to the points of the graph). As can be seen from Fig. 5, there is low correlation between pu V/Hz and Torque Ratio.

TABLE IV
Torque Ratio (**T_{PK}/T_L**)

Facility	1	2	3	4	5	6	7	8	9	10	11	12
Torque Ratio (T_{PK}/T_L)	4.12	2.38	2.48	1.97	1.87	1.62	2.08	1.50	21.74	2.39	1.89	1.79
pu V/Hz	0.3622	0.3054	0.3260	0.1489	0.2360	0.2939	0.3201	0.2635	1.2074	0.6178	0.6644	0.3838

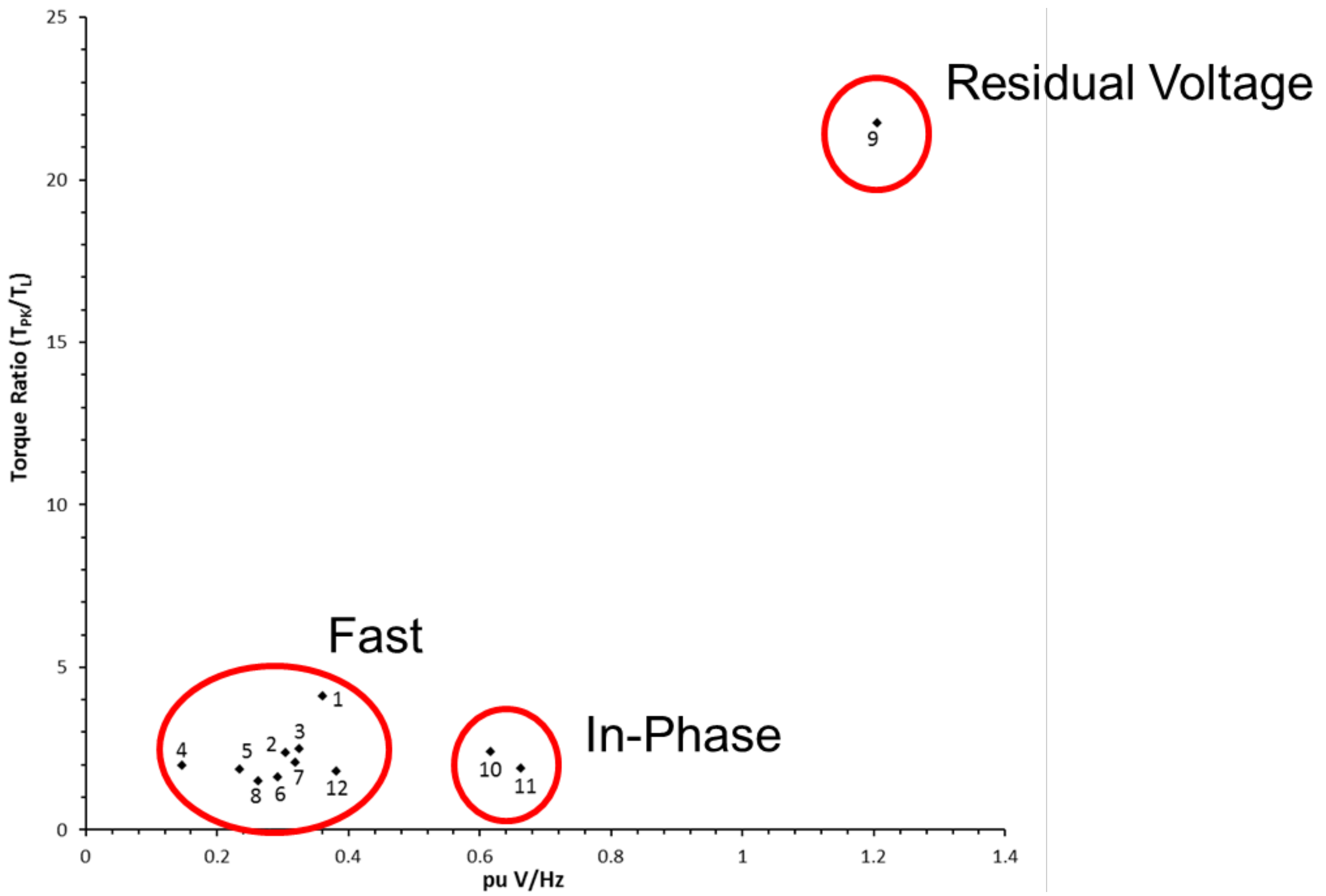

Fig. 5 pu Volts/Hz Vs Torque Ratio (T_{PK}/T_L)

According to ANSI C50.41, the transient torques during improper transfers can reach 20 pu. In Table IV and Fig. 5, the Facility 9 results demonstrate this with a Torque Ratio of 21.74 for a Residual Voltage Transfer close at 128.4 degrees. Yet the ANSI C50.41 limit of 1.33 pu V/Hz would give this Residual Voltage Transfer a passing grade at 1.2074 pu V/Hz.

The above observations indicate that the ANSI C50.41 limit of 1.33 pu V/Hz is not a good measure of motor torque.

Now a comparison is made between Torque Ratio and the Max Transfer pu Power as a criterion for motor bus transfer. Considering Facility 1 and Facility 9 cases from Tables II and IV, it can be seen that the Max Transfer pu Power is almost the same (21.5 for Facility 1 and 23 for Facility 9) whereas the motor Torque Ratios are vastly different (4.12 for Facility 1 and 21.74 for Facility 9). In other words Max Transfer pu Power is not a good indicator of motor torque.

In conclusion, the pu V/Hz calculation may not give a good indication of the motor torque, and the use of the ANSI 50.41 limit of 1.33 pu V/Hz as a criteria for motor bus transfer is questionable. Motor Torque Ratio can be calculated using the voltage and current waveforms recorded at transfer, and can indicate if a transfer is performed within safe motor torque design limits. The Residual Voltage Transfer where the phase angle and slip frequency are ignored can produce dangerously high torques. The In-Phase Transfer keeps motor torque well within safe limits, and is a good choice when Fast Transfer is not possible due a large initial angle.

XII. REFERENCES

[1] ANSI/NEMA C50.41-2012, *Polyphase Induction Motors for Power Generating Stations*, NEMA, Rosslyn, VA.
[2] Jon Gardell, Chair, J9 Working Group Report, IEEE Power System Relaying Committee, "Motor Bus Transfer Applications Issues and Considerations," May 2012.
[3] R. D. Pettigrew, et al, Motor Bus Transfer, *IEEE Transactions on Power Delivery*, Vol. 8, No. 4, Oct. 1993.
[4] W.G. Hartmann, T.R. Beckwith, "Test Results for Fast and In-Phase Transfers," Oct. 2014.
[5] S. E. Zocholl, Tutorial: "From the Steinmetz Model to the Protection of High Inertia Drives," September 2006

XIII. VITA

Thomas R. Beckwith received a Bachelor of Science degree in Electrical Engineering (BSEE) from Case Western Reserve University and a Master of Business Administration (MBA) degree from the University of South Florida. He is a member of the IEEE PES and the IEEE IAS. Tom has served on working groups in the Power System Relaying Committee since 1972. He was the chair of the working group that produced IEEE C37.90.1-2012 Standard for Surge Withstand Capability (SWC) Tests for Relays and Relay Systems Associated with Electric Power Apparatus. Tom is a co-inventor of a 1993 U.S. patent on a Multifunction Protective Relay System. He is presently CEO of Beckwith Electric Co., Inc. and previously held positions as Production Manager, Vice President of Sales and Marketing and President of the Beckwith Engineering Services and Training (BEST) division. Since 1970, Tom has served as R&D Design Engineer, Systems Engineer, and Field Commissioning Engineer.

Dr. Murty V.V.S. Yalla has been with Beckwith Electric Co. since 1989 and presently holds the position of President. He was Vice President of R&D/Engineering from 1994 to 2004. Dr. Yalla received a Bachelor's degree in Electrical Engineering from Jawaharlal Nehru Technological University, India; a Masters in Electrical Engineering from Indian Institute of Technology, India; and a Ph.D. in Electrical Engineering from the University of New Brunswick, Canada. Dr. Yalla has published several research papers in international journals on digital protection and holds five U.S. patents in digital controls and protective relays. Dr. Yalla is the Deputy Technical Advisor to the United States National Committee (USNC) of the International Electrotechnical Commission (IEC, Geneva, Switzerland) Technical Committee 95. He is a U.S. delegate and the chairman of the IEC TC 95 MT4 which develops functional standards for Measuring Relays and Protection Equipment. Dr. Yalla was a U.S. delegate to the International Council on Large Electric Systems (CIGRÈ, Paris, France) Working Groups B5.04, Modern Techniques for Protecting and Monitoring Generating Plants, and B5.05, Modern Techniques for Protecting, Controlling and Monitoring of Power Transformers. He was also a member (subject matter expert) of the North American Electric Reliability Corporation (NERC) System Protection and Control Subcommittee (SPCS).

Dr. Yalla was elected to IEEE Fellow in 2006 and was the Chairman of the Rotating Machinery Protection Subcommittee. He was the chairman of the working group which developed IEEE Standard C37.102-2006 "Guide for AC Generator Protection;" co-author of an IEEE PES tutorial "Protection of Synchronous Generators;" and chairman of the working group which received the IEEE PES Working Group Recognition Award in 2004 for an outstanding technical report "Application of Peer-to-Peer Communications for Protective Relaying." Dr. Yalla received the IEEE Florida Council Outstanding Engineer Award in 2005, and the IEC 1906 Award in 2010 which honors IEC experts around the world.