EXPANDED FIELD DATA ANALYSIS IN SUPPORT OF A TORQUE-BASED MOTOR BUS TRANSFER CRITERION

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Abstract – The ANSI/NEMA C50.41 Standard, "Polyphase Induction Motors for Power Generating Stations" states, "Induction motors are inherently capable of developing transient current and torque considerably in excess of rated current and torque when exposed to out-of-phase bus transfer." Further, "The magnitude of this transient current and torque may range from 2 to 20 times rated." This suggests a criterion related to a multiple of rated full load torque. Since a motor bus is comprised of an aggregate of different motors and loads, it is unrealistic to create an industry criterion for measuring the severity of the transfer of the aggregate bus based on individual motor rated torques. Data from a large number of live motor bus transfer events at industrial facilities were analyzed with a new transfer metric that is based on the ratio of the aggregate peak torque at transfer to the aggregate running torque just before transfer. These Torque Ratio results were scrutinized based on the C50.41 torque range from 2 to 20 times rated, where 2 would be good and 20 very bad, and then were compared with the C50.41 per unit Volts/Hertz criterion, calculated at the instant of transfer, which is presently used to determine an acceptable transfer. The calculation method is presented with the theory and mathematics employed, and is verified with simulation of a representative induction motor. Analyzing field cases, calculating Torque Ratio (T_{PK}/T_L), and comparing with the per-unit Volts/Hertz value, will demonstrate the validity of this Torque Ratio metric for determining an acceptable limit for transfer.

Index Terms **–** Motor Bus Transfer (MBT), Fast Transfer, In-Phase Transfer, Residual Voltage Transfer, Main-Tie-Main.

I. INTRODUCTION

To maintain process continuity 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. The basic bus structures under which motor bus transfer is applied within refineries were described in the 2015 IEEE PCIC paper, "Motor Bus Transfer System Performance Testing and the Search for a New Transfer Success Criterion" [1].

The costly consequences of a failure to transfer, or hard transfers with cumulative damage to motors and motor loads, are not acceptable. For years, the petrochemical industry has been content to apply the 1.33 pu V/Hz criterion from ANSI/NEMA C50.41 as a maximum acceptable limit for the design of critical process motor bus transfer systems. This standard suggests that somehow "calculations or tests should be performed by the user to determine the expected vectorial volts per hertz" and that "The results of the calculations shall be used to determine whether these requirements are met before fast transfer or reclosing is used on the system." Furthermore, ANSI/NEMA C50.41-2012 clause 14.3 states, "test conditions should account for any phase angle difference between the incoming and running power supplies" [2].

The system phenomena that exist or occurred just before the initial source breaker is tripped, and indeed may have precipitated the transfer to the alternate source, are responsible for these initial phase angle differences, and are well documented in the 2015 IEEE PCIC paper [3]. Given the wide range of initial angles that may occur, and the wide range of motor, size, intertie, and loading on motor buses, credible calculations are impractical. And no company is going to do calculations for every motor bus "to determine whether these requirements are met before fast transfer or reclosing is used on the system" [4]. The best that the industry has been able to do is apply the pu V/Hz criterion after a live, in-service transfer or reclosing of the bus system with multiple motors.

However, there is no way to apply the ANSI/NEMA C50.41 pu V/Hz criterion to individual motors for live in-service transfers, as individual motor breakers don't operate during transfer, so the resultant pu V/Hz measure cannot be calculated on an individual motor basis. However the pu V/Hz criterion can be calculated for the aggregate motor bus at the point of transfer, and this is published in Table A-I, MBT Field Results of live in-service results. This value can be calculated at each facility to judge compliance of the transfer system during actual planned or emergency transfers.

The proposed Torque Ratio criterion is offered as a replacement for the pu V/Hz criterion, and will likewise be employed to assess the results of live in-service transfers, calculated for the aggregate motor bus. This proposed Torque Ratio at Transfer is the Peak Motor Torque (T_{PK}) after the transfer, expressed as a multiple of Motor Torque under steady-state load prior to the transfer (T_L). This aggregate Torque Ratio multiple could be compared to the maximum specified multiple of rated torque at full load for the motor bus. This Torque Ratio can also be calculated for individual motors on the bus using oscillography from the digital motor protection relays on each motor. As a ratio, it even measures correctly regardless of the aggregate load levels, as the higher the load torque prior to transfer, the higher the peak torque at transfer, up to the maximum multiple of rated full load torque. Failure to monitor torque levels at transfer, and take measures to avoid damaging torques under all possible conditions, could ultimately lead to premature motor failure and loss of critical process motor loads.

Published in May 2012, the IEEE Power System Relaying Committee (PSRC) Report, "Motor Bus Transfer Applications Issues and Considerations" [5], describes three methods of Open Transition (break-before-make) Transfer. 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 are designed to trip the old source breaker before closing the new source breaker. Two modes are employed for Open Transition Transfers; the Sequential and the Simultaneous Mode. Sequential Mode ensures the Old Source Breaker is tripped before initiating the supervised close of the New Source Breaker. Simultaneous Mode simultaneously trips the Old Source Breaker while initiating the supervised close of the New Source Breaker. With this mode, a breaker failure scheme is required if the Old Breaker fails to trip, as it is frequently unacceptable for the two incoming sources to be paralleled.

II. 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, from a number of facilities around the world. These were not staged test transfers, but were captured with the facilities fully in service. Some were live final commissioning transfers, possibly involving new switchgear with the process fully in operation. Many were live in-service transfers as a result of some kind of abnormality, such as a problem with one of the incoming sources. Oscillographs from additional facilities have been added to the original data on 12 facilities from the paper, "A New Torque-Based Motor Bus Transfer Success Criterion," published in August of 2015 [6]. The data from the analysis of the oscillographs are tabulated in Table A-I and explained in detail in the following sections.

First, the results are compared with the present ANSI/NEMA C50.41 Standard criteria. A Torque Ratio criterion is then developed and derived from sound theory, which could be applied to oscillographic data previously recorded for all the transfers studied, to gauge the relative level of severity of the transfers.

III. MOTOR BUS TRANSFER FIELD OBSERVATIONS COMPARED TO ANSI / NEMA C50.41

Although the Fast and In-Phase (Synchronous) Transfer methods were both enabled, the results showed that Fast Transfers occurred in twenty-six events, and In-Phase Transfers occurred in six events. All of the Synchronous Transfer breaker close commands occurred at voltages above which the Residual Voltage Transfer undervoltage element would have operated. Although not advisable, three of the four Residual Voltage Transfer events occurred when the Synchronous Transfer methods were purposely disabled by the end user during commissioning testing, so the results for a Residual Voltage Transfer could be observed.

For years, ANSI/NEMA C50.41 Polyphase Induction Motors for Power Generating Stations [7] 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 the live in-service field results yields the following observations with regard to the requirements of ANSI/NEMA C50.41 and to petrochemical industry bus transfer practices in general.

The Fast and In-Phase (Synchronous) Transfer methods produce results that fully comply with b) and c), previously stated, from ANSI/NEMA C50.41.

Two of the six In-Phase transfer cases completed the transfer within the 10 cycle limit of ANSI/NEMA C50.41. However, four In-Phase Transfer results show that, in Facilities 11, 16, 17, and 31, with pu V/Hz values between 0.4579 and 0.6644 which are well below the 1.33 pu V/Hz limit, the "10 cycles or less" criteria must not be applied to the In-Phase Transfer method. Due to the aggregate inertia of the motors on the bus, it just may take more than 10 cycles for the motors to rotate back into synchronism and experience a perfectly good transfer.

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.

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) [8], with zero initial slip frequency (S_{INIT}), the angle movement ($\Delta Ø$) in 10 cycles (T), per equation (1), is a dangerous 100°.

$$\Delta Ø = 360(S_{INIT}+0.5R_S T)T \qquad (1)$$

The six In-Phase Transfers that were completed between 0.4597 and 0.6644 pu V/Hz, were transferred at angles of -7.7°, 7.1°, 2.2°, -1.1°, 5.8°, and -3.6°. Three of the four Residual Voltage Transfer cases were completed at 1.2074, 1.3395, and 1.2964 pu V/Hz at angles of 128.4°, 129.8°, and 174.0°. The In-Phase Transfers occur at higher voltages, at much lower slip frequencies, and coupled with the synchronous closure, provide a far gentler transfer than the “blind” Residual Voltage method. In the “spin of the roulette wheel”, FACILITY 36 seems to have gotten lucky, closing at 0.7746 pu V/Hz with a transfer after 77.2 cycles, at an angle of -47.7°.

Residual Voltage Transfers provide the least opportunity for maintaining continuity of critical process motor 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 high reacceleration current and associated torque.

Concerns have arisen 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 since the pu V/Hz calculation measures only voltage phenomena, completely ignoring inrush current levels at transfer, it cannot possibly address the torques the motors are experiencing. 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.

ANSI/NEMA C50.41 clearly states, “Induction motors are inherently capable of developing transient current and torque considerably in excess of rated current and torque when exposed to out-of-phase bus transfer… The magnitude of this transient current and torque may range from 2 to 20 times rated… [9]”

Yet ANSI/NEMA C50.41 offers no limit on the ratio of the transfer torque compared to rated torque. This mention of motor bus transfer transient currents and torques as a multiple of rated values led to an investigation of the transfer inrush voltage and current sine waves in the time domain. Treating the aggregate motor bus as a single motor, this is used to calculate the torque on such an individual motor at the peak of transfer and before transfer. This could be considered as another way to evaluate the success of a transfer of the aggregate motor bus from values available for the overall transfer.

IV. A NEW METRIC FOR ASSESSING MOTOR BUS TRANSFERS

The original FACILITY 1 through 12 oscillographic records [10], and now an additional 24 records of live motor bus transfers, are analyzed to derive a new transfer metric, based on the voltage and current during inrush at the close of the new source breaker. These time domain waveforms are used 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. It could also be used to measure and study the torque effect of the transfer on the individual connected motors.

This motor bus transfer metric uses the voltage and current signals to calculate the power drawn by the motor and the corresponding Torque Ratio between the peak air gap torque after the transfer and the air gap torque, under steady-state load, prior to the transfer.

A. Motor Air Gap Torque Calculation

The torque produced is equal to the power transferred through the air gap (P_{AG}) divided by the synchronous speed (ω_S):

$$T = P_{AG}/\omega_S \qquad (2)$$

This assumes all losses (copper losses, iron losses, friction and windage losses) are neglected.

The air gap torque is calculated for two different conditions and then a ratio is calculated:

- Motor Torque under steady-state load prior to the transfer (T_L)
(uses current signal taken from the existing source along with the motor bus voltage signal)
- Peak Motor Torque (T_{PK}) after the transfer has taken place
(uses current signal taken from the new source along with the motor bus voltage signal)
- The ratio T_{PK}/T_L is calculated

Calculation of power input to the motor requires voltage applied to the motor and current drawn by the motor. These signals are obtained from the oscillographs recorded during actual bus transfer operations from the field. The voltage and current phasors are calculated using the following recursive discrete Fourier transform algorithm from the sampled values of voltages and currents recorded in the oscillographs:

Voltage: $V_k^r = V_{k-1}^r + \frac{2}{N}\ (v_k - v_{k-N}) \cos\frac{2\pi k}{N}$ and $V_k^i = V_{k-1}^i + \frac{2}{N}\ (v_k - v_{k-N}) \sin\frac{2\pi k}{N}$ (3)

Current: $I_k^r = I_{k-1}^r + \frac{2}{N}\ (i_k - i_{k-N}) \cos\frac{2\pi k}{N}$ and $I_k^i = I_{k-1}^i + \frac{2}{N}\ (i_k - i_{k-N}) \sin\frac{2\pi k}{N}$ (4)

where

v_k and i_k are the sampled values of voltage and current signals

N is the number of samples in one cycle of fundamental frequency (50 or 60 Hz). N=32 is used

$\bar{V} = (V_k^r + j\ V_k^i)$ is the voltage phasor, and

$\bar{I} = (I_k^r + j\ I_k^i)$ is the current phasor at k_{th} sample.

Now power drawn by the induction motor at k_{th} sample is given by the following equation:

$$S_k = P_k + jQ_k = 3\ V\ I^* = 3\ (V_k^r + j\ V_k^i) \times (I_k^r - j\ I_k^i) \quad (5)$$

The real power (P_k) is given by:

$$P_k = 3\ (V_k^r\ I_k^r + V_k^i\ I_k^i) \quad (6)$$

When three-phase sampled values are available, the power can be computed using the voltage phasors ($\overline{\mathrm{VA}}$, $\overline{\mathrm{VB}}, \overline{\mathrm{VC}}$) and current phasors ($\overline{\mathrm{IA}}$, $\overline{\mathrm{IB}}, \overline{\mathrm{IC}}$) from all three phases:

$$P_k = \left(VA_k^r\ IA_k^r + VA_k^i\ IA_k^i\right) + \left(VB_k^r\ IB_k^r + VB_k^i\ IB_k^i\right) + \left(VC_k^r\ IC_k^r + VC_k^i\ IC_k^i\right) \quad (7)$$

Neglecting the stator core and copper losses, the power P_k can be considered as the power transmitted through the air gap.

The air gap torque at the k_{th} instant is calculated as follows:

$$T_k = P_k/\omega_s \quad (8)$$

where

ω_s is the synchronous speed in radians per second.

B. *Motor Air Gap Torque Example*

As an example, the torque time curve is plotted for the recorded motor bus transfer case from FACILITY 5 as shown in Fig. 1. In this figure, the air gap torque prior to the transfer is denoted as T_L and the peak air gap torque after the transfer is denoted as the T_{PK}. From these two values, the Torque Ratio is calculated.

The same analysis is repeated for all 36 cases, and the results are tabulated in Tables I and A-I. The Torque Ratio (T_{PK}/T_L) and the pu V/Hz values are plotted on a scatter chart shown in Fig. 2 for each of the facilities from 1 to 36.

V. MBT FIELD OBSERVATIONS, TORQUE RATIO VS. PU V/HZ

As can be seen from Fig. 2, there is low correlation between pu V/Hz and Torque Ratio. Upon inspection of Fig. 2 and Table I, the In-Phase Transfer cases (Facilities 10, 11, 16, 17, 30 and 31) have higher pu V/Hz values, but do not have higher Torque Ratios (T_{PK}/T_L). In fact, the Torque Ratios for the six In-Phase Transfers fall right in the middle of the Torque Ratios for all the Fast Transfers. It is clear that the higher calculated value of pu V/Hz in these cases is affected by a large voltage magnitude difference rather than a large phase angle difference. In reality, however, the real power exchange (which is responsible for the motor torque) between the source and the connected motor during reclosing transients is far more related to the phase angle difference rather than the voltage difference.

All of the twenty-six Fast Transfers were completed between 0.0773 (FACILITY 29) and 0.9471 pu V/Hz (FACILITY 26), all well under the ANSI/NEMA C50.41 limit of 1.33 pu V/Hz, and at Torque Ratios from 1.15 (FACILITY 29) to 5.34 (FACILITY 27). Seventeen of the Fast Transfers were completed with Torque Ratios between 1.15 and 2.85, with the remaining nine between 3.76 and 5.34.

A. *Initial 30° Phase Shift Mismatch Between Source Transformers*

An interesting set of conditions, reported in the 2012 IEEE PSRC Report [11], existed at a power plant with 10 separate motor buses, identified as FACILITY 18 through FACILITY 27. Each bus experiences an initial phase angle of 30° due to the phase shift mismatch between the two source transformers. For this reason, the end user could not risk a Simultaneous mode transfer where a breaker failure would even momentarily parallel the two out-of-phase transformers. Choosing Sequential mode transfer ensures that the Old Breaker has opened before attempting to close the New Breaker. But the mismatched transformers now present another problem. When the motor bus transfers one way, the initial angle is +30°, and once disconnected, the motor bus angle will rotate nicely toward 0°. The problem occurs when the bus transfers the other way, the initial angle is -30°, and once disconnected, the motor bus angle will move away from zero, and rotate 330° to arrive at the first zero crossing. An In-Phase Transfer would easily be able to perform a smooth transfer but for the Low Inertia, rapidly decaying nature of the motors on the bus, and by the time the angle arrived at the first zero crossing, the voltage would be too low, and the motors would drop out. The solution for the end user was to set the Fast Transfer Phase Angle Limit to 40°, so with both 30-degree initial angles within this window, the transfer can occur as soon as the Old Breaker opens. Since the motors are moving towards zero degrees, transfers starting at +30° will close at smaller angles (9.5° to 12.5°) and Torque Ratios (1.57 to 1.91), and those starting at -30° and moving away from zero degrees will close at larger angles (-47.3 to -60.9) and Torque Ratios (3.76 to 5.34).

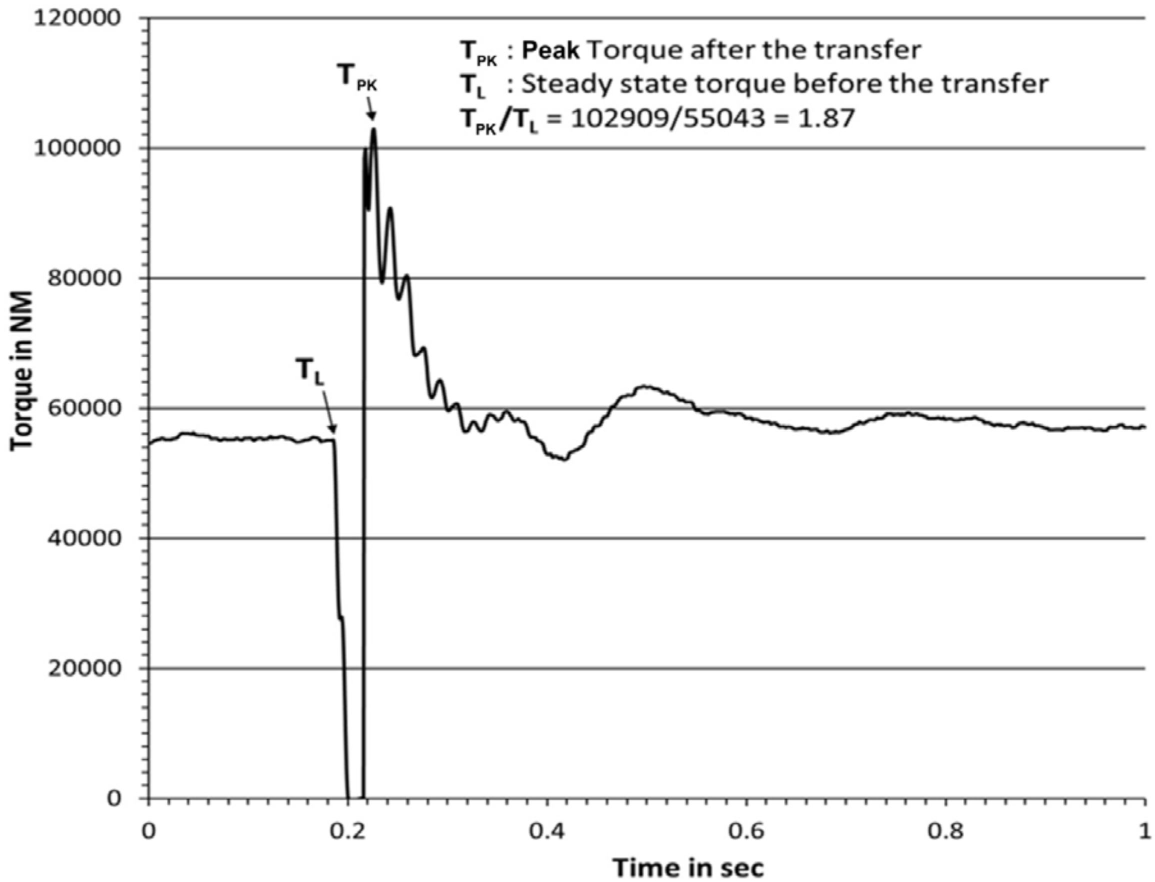

Fig. 1 Motor Air Gap Torque, Before and After Transfer

B. Comparison of In-Phase to Residual Voltage Transfers and Torque Ratio vs. pu V/Hz

According to ANSI/NEMA C50.41, out-of-phase bus transfers develop transient currents and torques that may range from 2 to 20 times rated. In Fig. 2 and Table II, the results demonstrate this with an In-Phase Torque Ratio of 1.89 at FACILITY 11, and Residual Voltage Torque Ratios of 11.31 and 13.83 at Facilities 9 and 35. Yet the ANSI/NEMA C50.41 limit of 1.33 pu V/Hz would give these Residual Voltage Transfer results a passing grade. The close angle is not monitored during residual transfer, and the angle can be large as depicted in FACILITY 9 and FACILITY 35. This method simply lets the motors spin down until the residual voltage is reached, and transfers with no regard as to the phase angle between the connected motors and the new source. Another residual transfer case (FACILITY 36) with a Close Angle of 47.7 degrees past zero (pu V/Hz 0.7746) results in a Torque Ratio of 2.63. In this case, as previously mentioned, the residual transfer got lucky due a low closing angle.

It is interesting to note that the FACILITY 11 In-Phase Transfer closed at about the same voltage as the Facilities 9 and 35 Residual Voltage Transfers, and the In-Phase slip frequency was around three times more than that of the two Residual Voltage Transfers. Obviously, the Residual Voltage Transfer “blind” Close Angles of 128.4 and 174 degrees are the culprits. Also, at around 48 cycles, the Residual Voltage Transfers are slow.

C. Comparison of Residual Voltage Transfers and Torque Ratio vs. pu V/Hz

The three completed Residual Voltage Transfers occurred at Facilities 9, 35 and 36 when the Synchronous Transfer Methods were purposely disabled, so the results for a Residual Voltage Transfer could be observed. Similar to the observations in the previous section, *B.*, the results in Fig. 2 and Table III, demonstrate a wide range of Close Phase Angles. The Close Voltages were about the same value. Facilities 9 and 35 recorded little frequency decay compared with significant frequency decay at FACILITY 36. But motor buses at Facilities 9 and 35 transferred at significant closing angles versus a small angle at FACILITY 36. The significant frequency decay at 36 had no corresponding effect on increasing the Torque Ratio. But, the high closing angles clearly do correlate with the high Torque Ratios. Yet, the measured pu V/Hz does not increase proportionately with the high closing angles and Torque Ratios.

TABLE I
TORQUE RATIO (T_{PK}/T_L) VERSUS PU V/HZ

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	11.31	2.39	1.89	2.85
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
FACILITY	13	14	15	16	17	18	19	20	21	22	23	24
Torque Ratio (T_{PK}/T_L)	1.83	4.65	4.82	3.77	3.75	4.39	4.70	1.91	4.70	1.58	1.57	3.76
pu V/Hz	0.3038	0.5464	0.5361	0.4597	0.4634	0.7909	0.7689	0.1892	0.8083	0.2249	0.2241	0.9251
FACILITY	25	26	27	28	29	30	31	32	33	34	35	36
Torque Ratio (T_{PK}/T_L)	1.83	4.28	5.34	1.21	1.15	2.80	2.17	1.46	1.79	2.05	13.83	2.63
pu V/Hz	0.1964	0.9471	0.7828	0.0851	0.0773	0.5291	0.5668	1.3395	0.3470	0.2952	1.2964	0.7746

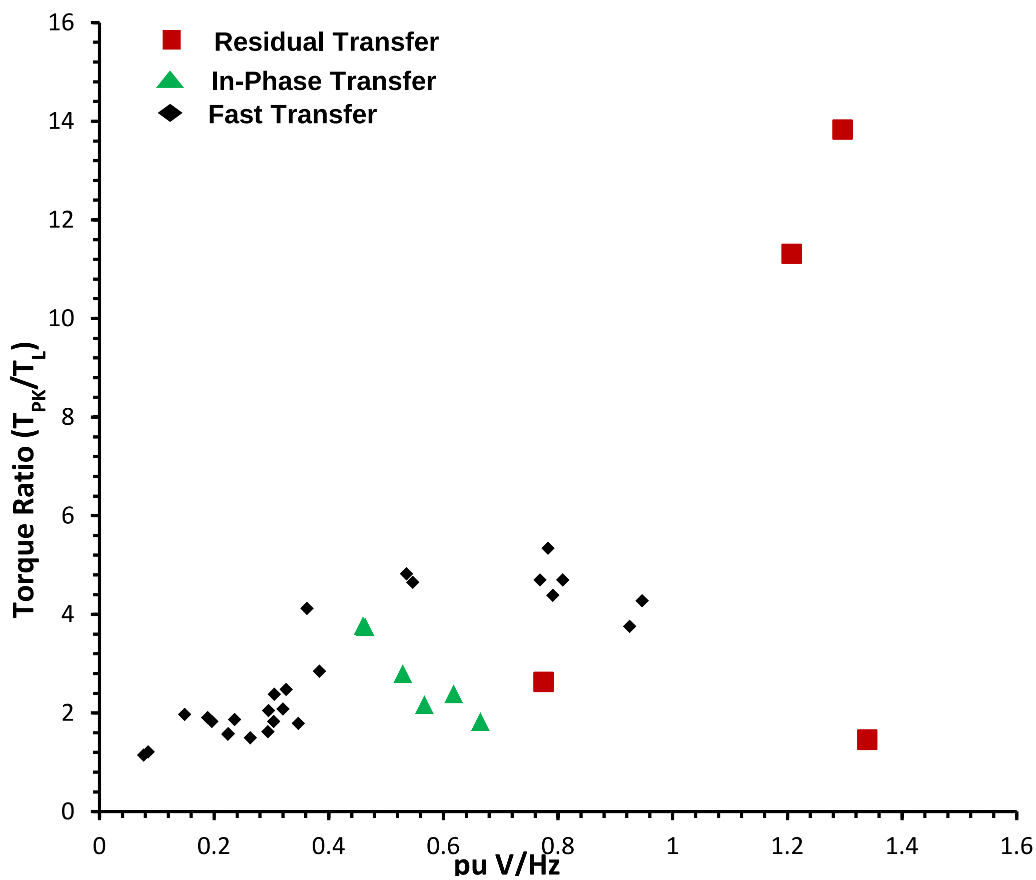

Fig. 2 Torque Ratio (T_{PK}/T_{TL}) versus pu Volts/Hz

TABLE II
IN-PHASE VS. RESIDUAL VOLTAGE RESULTS

FACILITY 11 In-Phase	FACILITY 9 Residual Voltage	FACILITY 35 Residual Voltage
37.7 Vac	34.7 Vac	35.0 Vac
-4.48 Hz	-1.66 Hz	-1.20 Hz
7.1°	128.4°	174.0°
Transfer=17.7 cycles	Transfer=48.7 cycles	Transfer=48.0 cycles
0.6644 pu V/Hz	1.2074 pu V/Hz	1.2964 pu V/Hz
Torque Ratio=1.89	Torque Ratio=11.31	Torque Ratio=13.83

TABLE III
RESIDUAL VOLTAGE RESULTS

FACILITY 9 Residual Voltage	FACILITY 35 Residual Voltage	FACILITY 36 Residual Voltage
34.7 Vac	35.0 Vac	31.4 Vac
-1.66 Hz	-1.20 Hz	-24.61 Hz
128.4°	174.0°	-47.7°
Transfer=48.7 cycles	Transfer=48.0 cycles	Transfer=77.2 cycles
1.2074 pu V/Hz	1.2964 pu V/Hz	0.7746 pu V/Hz
Torque Ratio=11.31	Torque Ratio=13.83	Torque Ratio=2.63

D. Initial -83.3° Source Mismatch, with Slow Residual Voltage Transfer Dropping VFD Motors, and Incorrect Setting Blocking In-Phase Transfer

Another Residual Voltage Transfer case (FACILITY 32) gave a surprising low Torque Ratio of 1.46 with a close angle of 129.8 degrees and pu V/Hz just above the limit at 1.3395. The transfer mode was set for Simultaneous due to the low inertia, rapidly decaying nature of the motors on the bus. But the initial phase angle between the motor bus and the new source was -83.3°, preventing any immediate attempt to perform a Fast Transfer. The In-Phase Transfer Method could have completed the transfer at the first zero phase coincidence with an Open Transfer Time of only 7.78 cycles, at a slip frequency of 13.3 Hz, but the slip frequency limit was customer-set at 10 Hz, so the In-Phase attempt was blocked. By the time the Residual Voltage Transfer was completed at an Open Transfer Time of 16.4 cycles, the slip frequency was -23.69 Hz. Upon close examination, it was determined that the major load on this bus was VFD motors. The steady state torque after the transfer was only 40% of the torque prior to the transfer. This indicates that the VFD motors dropped off due to the extended time it takes to complete a Residual Voltage Transfer. The large inrush current seen immediately after the transfer was about 12.5 times the load current prior to the transfer. This was the transformer inrush current where the majority of current is due to the reactive component rather than the real component. That is the reason why the peak torque immediately after the transfer was only 1.46 times the torque prior to the transfer, as that torque is only a result of the low real current component after the transfer. A higher setting of the slip frequency limit to 15.0 Hz would have permitted the In-Phase Transfer to close near zero degrees. As the VFD was equipped with the necessary regenerative capability to ride through what would have been a momentary 7-cycle drop in voltage, restoring the voltage that had decayed to a minimum of 51 Volts would have kept the VFD with all its motors in service.

E. Initial 115° Source Mismatch, In-Phase Transfer with a Torque Ratio of 2.39

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°. As in the previous case, 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 with a Torque Ratio of 2.39. 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.

F. Simultaneous Transfer Mode

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 0.3622 pu V/Hz with a Torque Ratio of 4.12. With motors and loads that are dragging down the frequency so rapidly, 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.

VI. CONCLUSIONS

It is the proven thesis of this paper that transfers that produce dangerously high Torque Ratios on the aggregate motor bus are given a passing grade by the ANSI/NEMA C50.41 pu V/Hz criterion. If it is torque that reduces the life expectancy and damages motors or driven equipment, or both, as suggested in the ANSI/NEMA C50.41 Standard, then the industry must use a torque-based criterion to assess if transfers are being completed within acceptable torque limits. While we leave it to the industry to determine a Maximum Torque Ratio Limit, it is clear that many transfers are successfully occurring at Torque Ratios between 1.21 and 2.85, with others between 3.75 and 5.34, but there are some Residual Voltage Transfers with Torque Ratios well above those values, at 11.31 and 13.83. Furthermore, some transfers with low Torque Ratios are given much higher pu V/Hz values than others with relatively equal Torque Ratios. Obviously, this is a serious flaw of the pu V/Hz criterion.

These observations indicate that the ANSI/NEMA C50.41 limit of 1.33 pu V/Hz is not a good measure of motor torque and may not protect motors from significant multiples of rated torque.

Unlike the Torque Ratio criterion, the resultant pu V/Hz measure cannot be calculated on an individual motor basis, as individual motor breakers don't operate, but only on the aggregate value between the motor bus and the new source at the instant of breaker closure. But even with a single motor on the bus, resultant pu V/Hz is not a measure of torque.

Therefore, the ANSI/NEMA C50.41 limit of 1.33 pu V/Hz as a criteria for motor bus transfer is of questionable use. The aggregate Motor Bus Transfer 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.

VII. REFERENCES

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VIII. VITAE

Dr. Murty V.V.S. Yalla has been with Beckwith Electric Co. since 1989 and presently holds the position of President. Dr. Yalla received a BSEE from Jawaharlal Nehru Technological University, India; a MSEE from Indian Institute of Technology, India; and a Ph.D. in Electrical Engineering from the University of New Brunswick, Canada. Dr. Yalla holds five U.S. patents in digital controls and protective relays.

Dr. Yalla is chair of the International Electrotechnical Commission (IEC, Geneva, Switzerland) Technical Committee 95, Measuring Relays and Protection Equipment. Dr. Yalla is Deputy Technical Advisor to the United States National Committee (USNC) of the IEC, and convener of IEC TC 95 MT4. Dr. Yalla was a U.S. delegate to the International Council on Large Electric Systems (CIGRÈ, Paris, France) for working groups on protecting and monitoring generating plants and power transformers. He was a member of the North American Electric Reliability Corporation (NERC) System Protection and Control Subcommittee.

Dr. Yalla is an IEEE Fellow for contributions in computer relays for power systems. As member of the IEEE Power System Relaying Committee (PSRC) he was Rotating Machinery Protection Subcommittee Chair. He was working group chair of IEEE Standard C37.102-2006 "Guide for AC Generator Protection;" IEEE PES tutorial co-author "Protection of Synchronous Generators;" and received the 2004 IEEE PES Working Group Recognition Award for outstanding technical report. Dr. Yalla received the IEEE Florida Council Outstanding Engineer Award in 2005, and the IEC 1906 Award in 2010 which honors IEC experts worldwide.

Thomas R. Beckwith received a BSEE from Case Western Reserve University and an MBA from the University of South Florida. He is a member of the IEEE PES and the IEEE IAS and has served on working groups in the Power System Relaying Committee since 1972. He was the chair of the working group 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. Presently CEO of Beckwith Electric Co., he previously held positions as Production Manager, Vice President of Sales and Marketing and President of Beckwith Engineering Services and Training (BEST). Since 1970, Tom has served as R&D Design Engineer, Systems Engineer, and Field Commissioning Engineer.

APPENDIX A

TABLE A-I
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	Torque Ratio T_{PK}/T_L
FACILITY 1	Simultaneous	FAST	-0.1	-20.0	-2.83	93.8	0.3622	1.3	4.12
FACILITY 2	Sequential	FAST	-10.8	-16.3	-0.19	100.4	0.3054	5.0	2.38
FACILITY 3	Simultaneous	FAST	-3.0	-18.5	-0.81	103.4	0.3260	3.3	2.48
FACILITY 4	Sequential	FAST	-0.8	-6.8	-0.23	107.9	0.1489	2.9	1.97
FACILITY 5	Simultaneous	FAST	-1.2	-12.6	-1.76	103.2	0.2360	1.3	1.87
FACILITY 6	Simultaneous	FAST	-1.1	-16.5	-2.25	102.0	0.2939	1.4	1.62
FACILITY 7	Sequential	FAST	-2.8	-17.1	-0.49	98.7	0.3201	2.9	2.08
FACILITY 8	Sequential	FAST	-2.2	-12.7	-0.38	99.0	0.2635	2.9	1.50
FACILITY 9	Sequential	Residual Voltage	152.4	128.4	-1.66	34.7	1.2074	48.7	11.31
FACILITY 10	Sequential	IN-PHASE $Ø_{INIT}$ =115°	55.0	-7.7	-2.77	44.4	0.6178	9.4	2.39
FACILITY 11	Sequential	IN-PHASE ØINIT=-0.1°	78.9	7.1	-4.48	37.7	0.6644	17.7	1.89
FACILITY 12	Simultaneous	FAST	-0.1	-20.3	-2.23	89.4	0.3838	1.7	2.85
FACILITY 13	Sequential	FAST	-2.2	-16.3	-0.47	100.4	0.3039	3.3	1.83
FACILITY 14	Simultaneous	FAST	-19.3	-33.1	-1.14	100.9	0.5464	6.6	4.65
FACILITY 15	Simultaneous	FAST	-16.8	-32.4	-1.36	101.0	0.5361	6.2	4.82
FACILITY 16	Sequential	IN-PHASE ØINIT=-13°	34.3	2.2	-2.07	62.7	0.4597	50.0	3.77
FACILITY 17	Sequential	IN-PHASE ØINIT=-9°	33.8	-1.1	-2.07	62.2	0.4634	50.6	3.75
FACILITY 18	Sequential	FAST	-32.6	-48.6	-0.74	108.1	0.7909	3.3	4.39
FACILITY 19	Sequential	FAST	-32.4	-47.3	-0.73	107.2	0.7689	3.3	4.70
FACILITY 20	Sequential	FAST	24.4	9.5	-0.36	106.6	0.1892	3.3	1.91
FACILITY 21	Sequential	FAST	-33.3	-50.9	-0.88	101.3	0.8083	3.4	4.70
FACILITY 22	Sequential	FAST	25.7	12.5	-1.98	106.2	0.2249	3.0	1.58
FACILITY 23	Sequential	FAST	26.5	12.1	-0.73	106.5	0.2241	3.2	1.57
FACILITY 24	Sequential	FAST	-34.6	-59.7	-1.37	98.1	0.9251	3.3	3.76
FACILITY 25	Sequential	FAST	26.6	10.1	-0.97	105.8	0.1964	3.2	1.83
FACILITY 26	Sequential	FAST	-34.2	-60.9	-0.88	100.7	0.9471	3.2	4.28
FACILITY 27	Sequential	FAST	-32.4	-49.0	-0.86	102.2	0.7828	3.3	5.34
FACILITY 28	Simultaneous	FAST	2.5	-4.1	-1.08	112.1	0.0851	1.0	1.21
FACILITY 29	Simultaneous	FAST	6.4	-3.7	-1.54	111.7	0.0773	1.3	1.15
FACILITY 30	Simultaneous	IN-PHASE ØINIT=50°	38.0	5.8	-2.70	54.5	0.5291	3.5	2.80
FACILITY 31	Simultaneous	IN-PHASE ØINIT=-80°	85.6	-3.6	-5.37	47.5	0.5668	19.9	2.17
FACILITY 32	Simultaneous	Residual Voltage	129.6	129.8	-23.69	33.2	1.3395	16.4	1.46
FACILITY 33	Simultaneous	FAST	0.0	-20.2	-2.58	103.8	0.3470	1.5	1.79
FACILITY 34	Simultaneous	FAST	0.0	-16.8	-2.26	103.6	0.2952	1.4	2.05
FACILITY 35	Simultaneous	Residual Voltage	-167.1	174.0	-1.20	35.0	1.2964	48.0	13.83
FACILITY 36	Simultaneous	Residual Voltage	56.8	-47.7	-24.61	31.4	0.7746	77.2	2.63