Motor Bus Transfer: Considerations and Methods

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***Abstract*—This paper addresses the types of motor bus transfer (MBT) available, explores its technical challenges, and analyzes the creation of proper settings when implementing an MBT system for power plant spinning motor auxiliary buses or industrial plant spinning motor buses. Classic approaches are described and conditions are explored that make these transfers proper or improper. Advanced implementations of MBT methodology that use high-speed sensing, decision making, and breaker control to account for the dynamic conditions in and about the plant, such as motor dispatch and loading, new source conditions, and faults are explored.**

***Index Terms*—Fast transfer, in-phase transfer, long-time transfer, motor bus transfer (MBT), residual transfer, sequential transfer, simultaneous transfer, source transfer.**

I. INTRODUCTION

TO MAINTAIN process continuity, motor buses may require transfer from a present source to a new source. The reasons for this may be fault clearing on the present source, deliberate transfer from a utility source to the onsite source during storm periods or for rate savings (and back to utility power at a later time), and deenergization of the present source for maintenance or construction. A simplified one-line diagram is shown in Fig. 1.

Motor bus transfer (MBT) schemes and systems are employed to maintain process continuity in processes served by large motors or aggregates of smaller and large motors. Smaller induction motors (generally 480 V) undergo very rapid voltage and frequency decay upon disconnection from a power source; therefore, the source-transfer type is generally a residual transfer, where the voltage on the motor bus is low or zero and the frequency is low or zero as the motors have coasted to a near halt or have stopped. The motors are then restarted.

Larger motors, of both the synchronous and induction variety, may require more comprehensive source-transfer strategies in order to avoid mechanical damage. The coastdown period and resultant voltage and frequency decay may take seconds, and unsupervised source transfer may cause damage. Mechanical damage may occur in the motor, the coupling to the load or the load itself, and is primarily caused by excessive torque. Therefore, the total mission of an MBT transfer system is not only to maintain process continuity but also to affect source transfers in such a manner as not to cause any damage to the motors and connected loads.

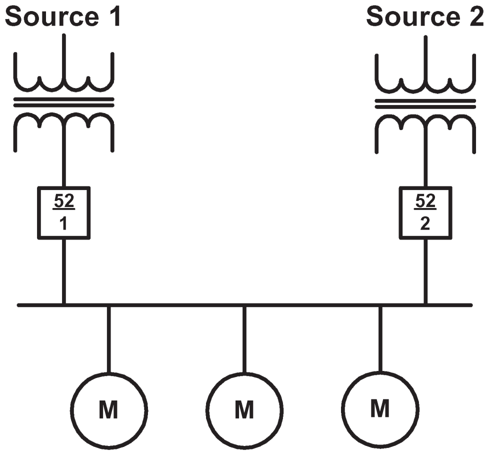

Fig. 1. Simplified MBT one-line diagram.

Referring to Figs. 2 and 3, a few generalizations can be made regarding the inertia of motor loads, motor size, and the mix of synchronous and induction motors.

1) *Inertia:* The higher the inertia of the aggregate motor loads on the motor bus, the more slowly the motor-bus frequency will decay during the disconnected coastdown period. That has a direct impact on how fast the phase angle changes. Low inertia loads will cause the phase angle to change quickly, as the frequency of the motor bus decays quickly, and the slip frequency between the motor bus and the new source quickly increases.
2) *Motor Size:* The larger the motor size, the longer the time the voltage will take to decay on an induction motor.
3) *Mix of Synchronous and Induction Motors:* Voltage will tend to decay much more rapidly on a motor bus with all induction motors. On a motor bus with a mix of synchronous and induction motors, the synchronous motors will attempt to hold up the voltage during the transfer interval.
4) *Loading:* The higher the load on the motors, the faster the motor-bus frequency will decay.

These parameters are key to analyzing the MBT issue and developing schemes to accomplish transfer that promotes process continuity while causing no damage to the motors or the loads.

An important value to decide the viability of MBT is the resultant volts per hertz (V/Hz). The resultant volts per hertz is derived from the volts per hertz vectors of the motor bus and the

Paper PID-05-19, presented at the 2004 IEEE Petroleum and Chemical Industry Technical Conference, San Francisco, CA, September 13–16, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Petroleum and Chemical Industry Committee of the IEEE Industry Applications Society. Manuscript submitted for review September 15, 2004 and released for publication November 19, 2005.

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Digital Object Identifier 10.1109/TIA.2005.863914

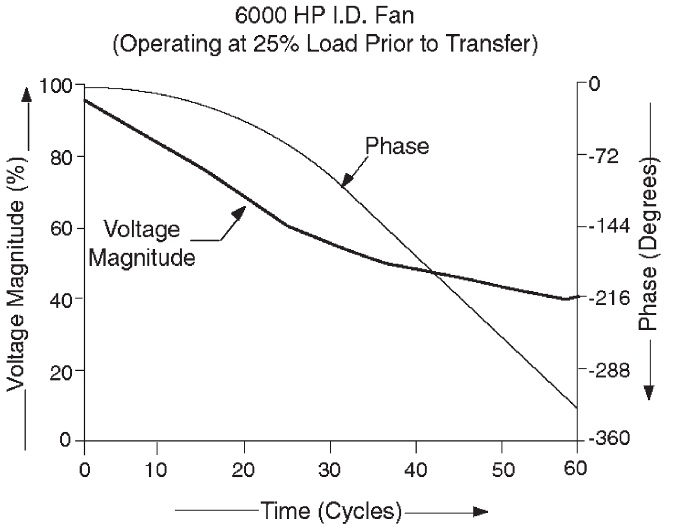

Fig. 2. Coastdown of high-inertia load on a large synchronous motor.

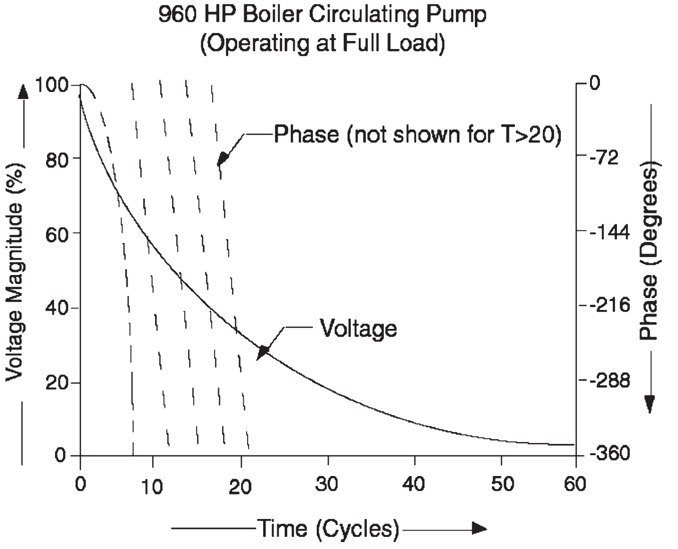

Fig. 3. Coastdown of low-inertia load on a large induction motor.

new source at the instant just prior to connection which must not exceed 1.33 V/Hz [1]. Pursuant to phase angle and voltage, and their effect on the resultant volts per hertz, some generalizations can be made.

1) *Phase Angle:* As the phase angle increases between the two sources, assuming the two source voltages are the same, the volts per hertz will increase.
2) *Voltage:* As the voltage difference between the two sources increases, assuming the phase angle between the sources remains the same, the volts per hertz will increase.

The resultant volts per hertz issue is exacerbated when the phase-angle difference increases and the voltage difference increases, as shown in Fig. 4. The following relationship in (1) defines this condition:

$$E_{\mathrm{R}} = \sqrt{E_{\mathrm{S}}^2 + E_{\mathrm{M}}^2 - 2E_{\mathrm{S}}E_{\mathrm{M}}\cos\theta} \tag{1}$$

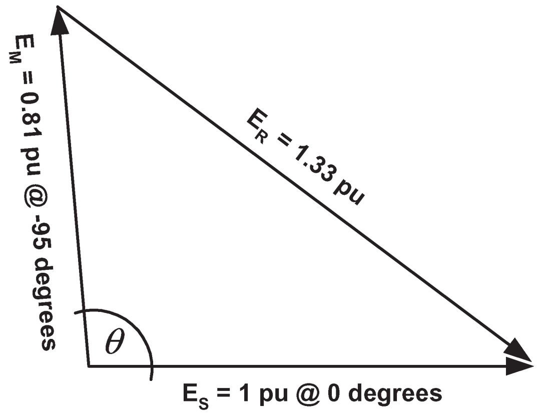

Fig. 4. Volts per hertz resultant from E_{S} and E_{M}.

where

E_{S} system equivalent volts per hertz;
E_{M} motor residual volts per hertz (on system base);
E_{R} resultant vectorial volts per hertz;
θ phase angle between the motor bus and new source at the instant prior to connection.

II. CLASSIC MBT METHODS

A. Hot Parallel, Fast, Residual, and Long Time

MBTs can be categorized as closed or open transition [2]. The closed transition involves brief paralleling of the sources. The closed-transition transfer is commonly referred to as a hot-parallel transfer. Open-transition transfers do not parallel the sources, and include fast, residual, and long time. The fast transfer can be subcategorized as simultaneous or sequential. All other transfers are sequential. Each is explored, along with the supervisions that may be applied, in the following passages.

1) Hot-Parallel Transfer: In a hot-parallel transfer, the new source is connected to the motor bus before the old source is tripped. The intent is to transfer sources without interruption. The phase angle and voltages from the motor bus and the new source are evaluated prior to the transfer to assure that the motor bus and the new source are in synchronism, or that the new source lags the old source to an acceptable amount. This method has gained a wide acceptance for routine-source transfers because transients on the motor bus are eliminated. There may be instances where the two sources may not be derived from the same primary source and a large standing phase angle may be present between them, precluding a hot-parallel transfer. Assuming that the phase-angle relationship of the two sources is acceptable, with the two sources paralleled, the currents flowing into and through the bus may violate the interrupt rating for the circuit breakers and the short-term withstand ratings source transformers. A fault occurring either on the bus or on one of the sources during the time the sources are paralleled can overstress the components of the bus system. The probability of this happening may be viewed as small; however, the consequences of such a fault occurring during the source paralleled operating interval should be thoroughly understood before the parallel transfer system is used.

2) Fast Simultaneous Transfer: In a fast simultaneous transfer, a trip command is issued to the present-source breaker and a close command is issued to the new-source breaker at the same instant. The phase angle and voltages from the motor bus and the new source are evaluated prior to the transfer to assure that the motor bus and the new source are in synchronism, or that the new source lags the old source at an acceptable amount. The close command is unsupervised. This is the fastest transfer type that does not deliberately parallel the sources. Due to the breaker operating-time variations and control-voltage variations, brief unintentional paralleling of the sources may occur.

3) Fast Sequential Transfer: In a fast sequential transfer, the present source is tripped, and as soon as the present-source breaker has started to open (typically indicated by an "early b" contact), a close command is issued to the new-source breaker. The close command may be supervised or unsupervised depending on the transfer method employed. This is the second fastest transfer type that does not deliberately parallel the sources.

Unsupervised closed commands used in the fast simultaneous and fast sequential transfers make certain assumptions about the phase angle and slip frequency between the decelerating motors, the plant, and the new source.

1) The transfer is affected before the phase angle between the new source and the motor bus increases to an undesirable value.
2) A fault did not occur on the present source, which may affect the phase angle at the instant the transfer sequence starts.
3) There will be a little change in the phase angle between the motor bus and the new source once the present source has been disconnected.
4) Any preconceived notions about the deceleration characteristics of the motor bus have not changed. Key characteristics would be the changes in the combined inertia of the motor loads and the changes in the mix of synchronous and induction motors.

A supervised closed command used in the fast sequential transfers can dynamically block the fast transfer, just after the present source is disconnected, if any of the following occurs.

1) A fault occurs on the present or new source, which may affect the phase angle at the instant the transfer sequence starts.
2) A fault occurs on the motor bus.
3) There is a large change in the phase angle between the motor bus and the new source once the present source has been disconnected [2].
4) Any preconceived notions about the deceleration characteristics of the motor bus have changed in that the deceleration has increased, therefore causing the phase angle to change rapidly. This would occur from a decrease in the inertia of the motor loads.

In order to make a blocking decision rapidly, specialized sync check equipment should be employed to make decisions on a moving phase angle in the shortest time possible, typically 1–2 cycles [3]. If the sync check equipment reacts too slowly, a transfer could be allowed when the phase-angle value is actually in violation of the setting [4]. An unsupervised fast sequential transfer is faster than a supervised fast sequential transfer as the transfer process must have a small delay built in to allow the sync check measurement and possible transfer blocking to occur.

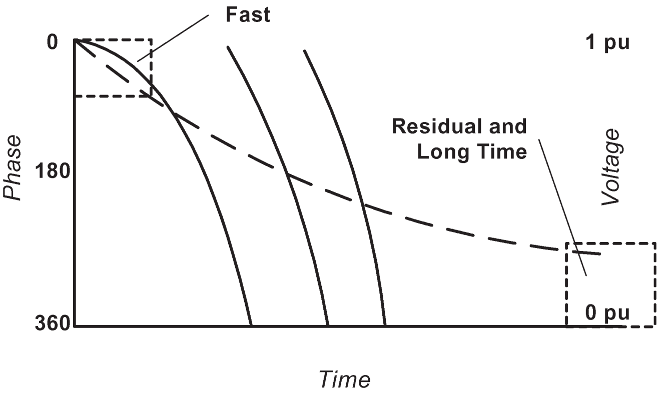

Fig. 5. Order of classic open transition MBTs.

4) Residual Transfer: In a residual transfer, the motor bus is connected to the new source after the voltage on the coasting motor bus falls to less than 0.25 pu. In this manner, no matter what the phase angle, the resultant volts per hertz will not exceed 1.33 V/Hz. This is the third fastest type of transfer type that does not parallel the sources. This type transfer, however, may not be fast enough to maintain process continuity, as certain motors loads that cause rapid stalling may necessitate a restart of the motors on the bus.

5) Long-Time Transfer: In a long-time transfer, the motor bus is connected to the new source after a time delay that would reflect that the voltage on the coasting motor bus has fallen to less than 0.25 pu. In this manner, no matter what the phase angle, the resultant volts per hertz will not exceed 1.33 V/Hz. This is the fourth fastest type of transfer type that does not parallel the sources. This type transfer, however, may not be fast enough to maintain process continuity, as certain motors loads that cause rapid stalling may necessitate a restart of the motors on the bus.

These open transition transfers would be attempted in the order they are presented, as shown in Fig. 5. The first possible transfer would be the fast transfer, which would be made if the phase angle between the motor bus and the new source is not too large. If that transfer was not made, a residual or long-time transfer would be initiated. Obviously, the fast transfers offer the greatest chance of process continuity, as the interruption period to the motors is short. By the time a residual or long-time transfer is initiated, the motors may have stopped against low inertia loads, such as positive displacement pumps or conveyors, and a process interruption may occur. In addition, if many motors must be started to restart the process, load shedding and staggered starting of the motors may have to be undertaken so as not to overload the capacity of the new source and cause unacceptable voltage sags during the restarting procedure.

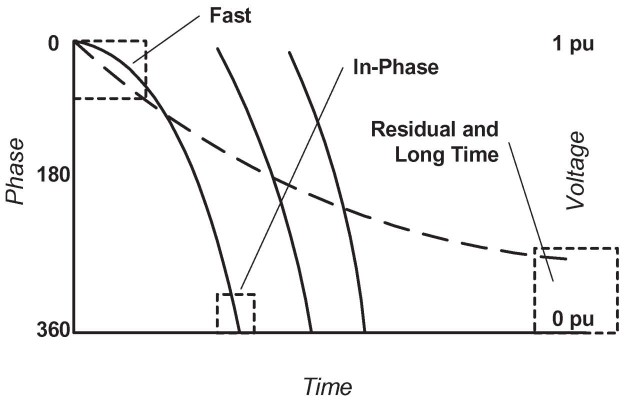

Fig. 6. Order of possible open transition MBTs.

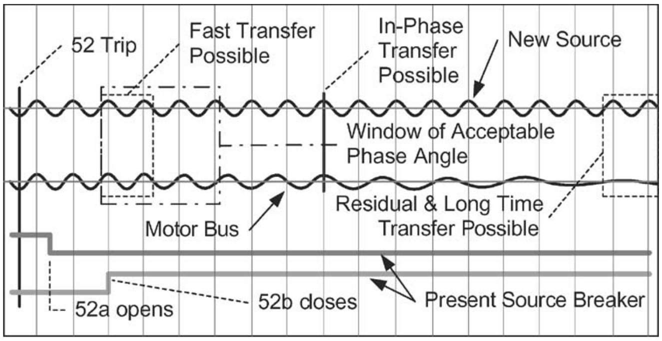

Fig. 7. Ringdown oscillograph representation.

III. ADVANCED MBT METHOD

A. In-Phase Transfer

There is a type of sequential transfer that may be applied if a fast transfer cannot be made, but before a residual or long-time transfer. It is called an in-phase transfer and offers an additional opportunity to transfer while the motors are still spinning and the likelihood of process interruption is minimized.

An in-phase transfer is defined as connecting a motor bus and the new source that have a slip frequency between them (the motor bus is coasting down) at the first 0° of phase coincidence. It is essentially a specialized type of automatic synchronizing under high slip frequency (typically from 0.5 to 10 Hz), and a rapidly decelerating motor-bus frequency (rapidly growing slip frequency). This requires the use of very fast measurement and output command techniques. As the slip frequency is changing rapidly due to the deceleration of the motor bus, calculation of the rate of change of frequency may be required in addition to examination of the instantaneous slip frequency when making the new-source closing command decision [4].

With the inclusion of the in-phase transfer, the first possible open transition transfer would be the fast transfer, followed by the in-phase transfer, followed by the residual and long-time transfers, as shown in Fig. 6. The fast transfer and the in-phase transfer offer the greatest chance of process continuity, as the interruption period to the motors is short.

Of possible concern with the in-phase transfer is the repeatability of the circuit-breaker closing time. Variances in this time from the value used by the MBT relay will cause an angular error to result. With fast breakers (typically 4-cycle closing time), a variance of 1 cycle in the closing time will cause an error in the predicted closing angle. However, when calculations for resultant volts per hertz are made, the effect of the angle error is small. See the Appendix for examples of this error.

IV. TRANSFER SEQUENCE ANALYSIS

A. Ringdown Examination

The fast transfer requires analysis of the expected conditions of the motor bus prior to transfer. Parameters that affect the decision to fast transfer or not include the change in phase angle and voltage during the open transition period. If the phase angle and voltage relationship would create an unfavorable volts per hertz, the fast transfer may not be permitted. If the conditions on the motor bus are variable, supervision of the fast transfer during the open period may be required so that a transfer or block transfer decision is made.

There are mathematical and empirical methods of determining the suitability of a motor bus for a fast transfer. The discussion of mathematical modeling is beyond the scope of this paper. We will explore an empirical method commonly called a "bus ringdown."

A bus ringdown involves the operation of the motor bus at expected nominal conditions, and then disconnecting the source from the bus and observing the frequency decay and voltage decay characteristics as the motors coastdown. A tool for recording and analyzing the ringdown is typically an oscillograph. Older technology offered lightwave oscillography, and newer technology offers digital oscillography, which may be included as part of newer digital metering and protection packages, or stand-alone digital fault and event recorders (DFR).

The oscillograph should examine specifically at least a single-phase voltage from the motor bus and the same single-phase voltage from the new source. The oscillographic record should start a few hertz prior to the disconnection of the present source to the motor bus and record until the motor-bus voltage decays to 0.25 pu. A representation of an oscillographic record used for analyzing a ringdown is shown in Fig. 7.

When viewing the ringdown oscillograph for MBT possibilities and settings of MBT equipment, there are several items to take into account.

1) If a fast simultaneous transfer is desired, the new-source breaker close command is issued at the same time as the present breaker trip command is issued.
2) If a fast sequential transfer is desired, the new-source breaker close command is issued when the 52b of the present-source breaker closes. If supervision by high-speed sync check is desired, the reaction time of the sync check element must be subtracted from the window of acceptable phase angle. Note that in Fig. 7, the fast-transfer window does not start until a finite time after the present-source 52b closes.
3) For all fast transfers, the fast-transfer window is limited by the acceptable phase angle using the volts per hertz calculation in (1). The phase-angle setting on the

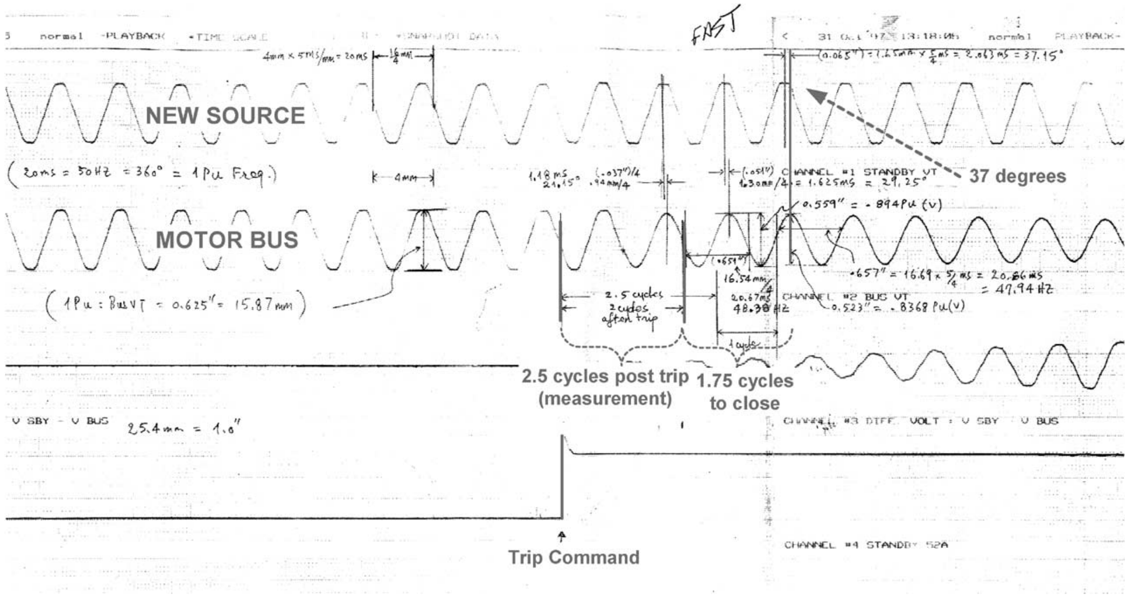

Fig. 8. Ringdown illustrating fast-transfer opportunity.

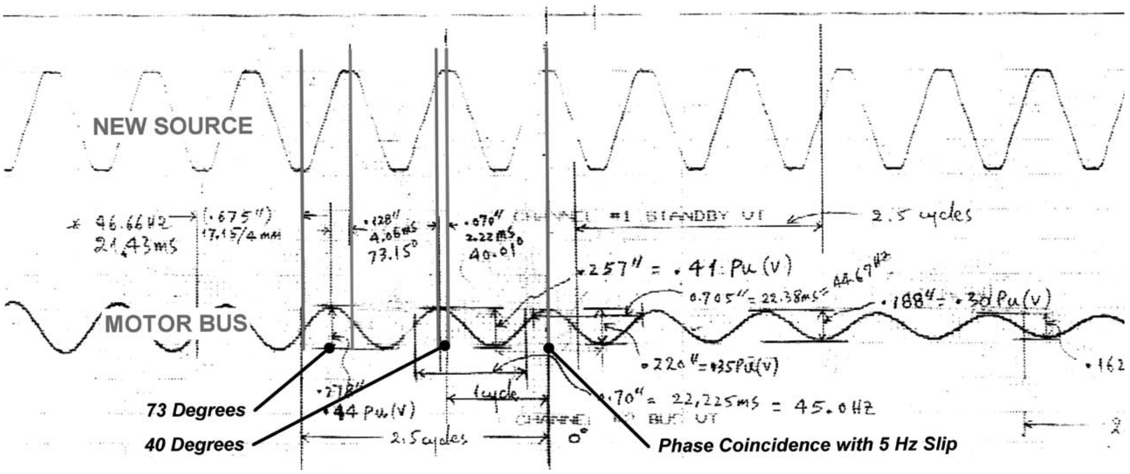

Fig. 9. Ringdown illustrating in-phase-transfer opportunity.

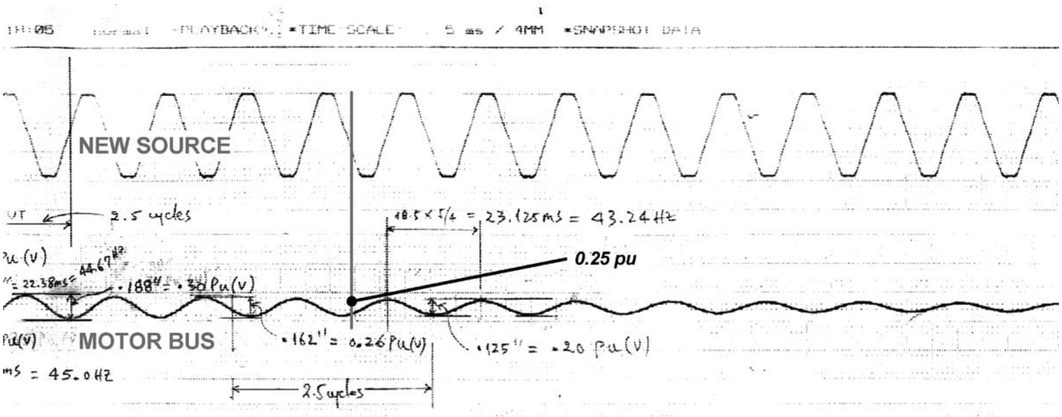

Fig. 10. Ringdown illustrating residual or long-time-transfer opportunity.

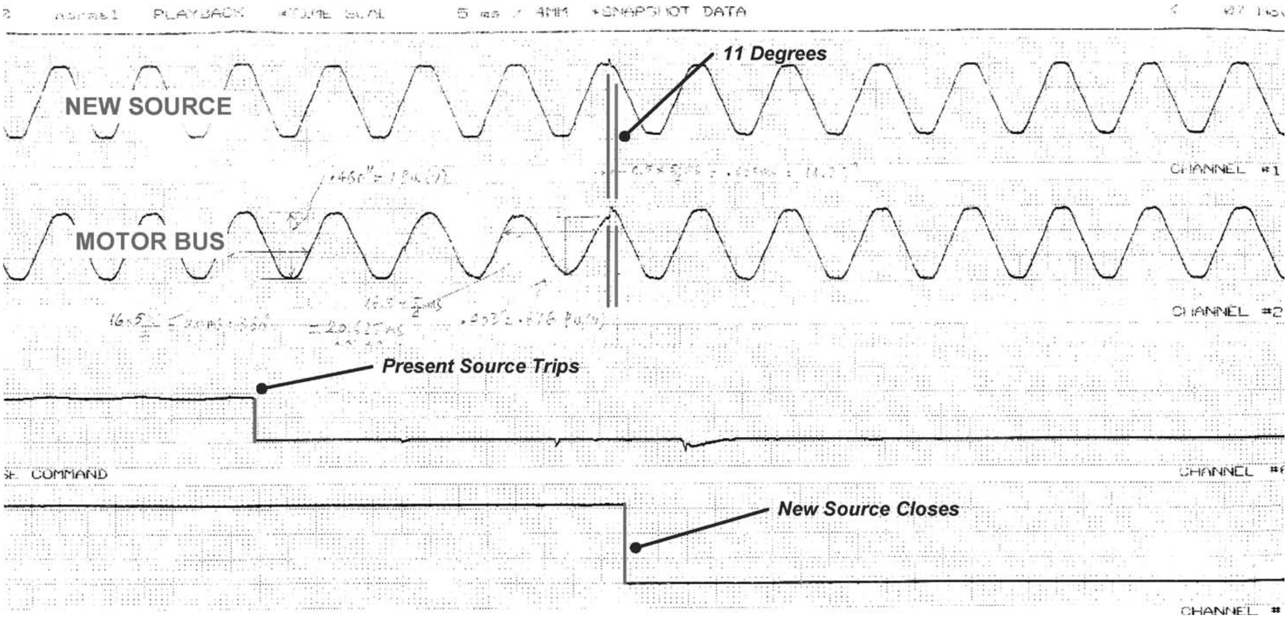

Fig. 11. Actual fast-transfer sequence.

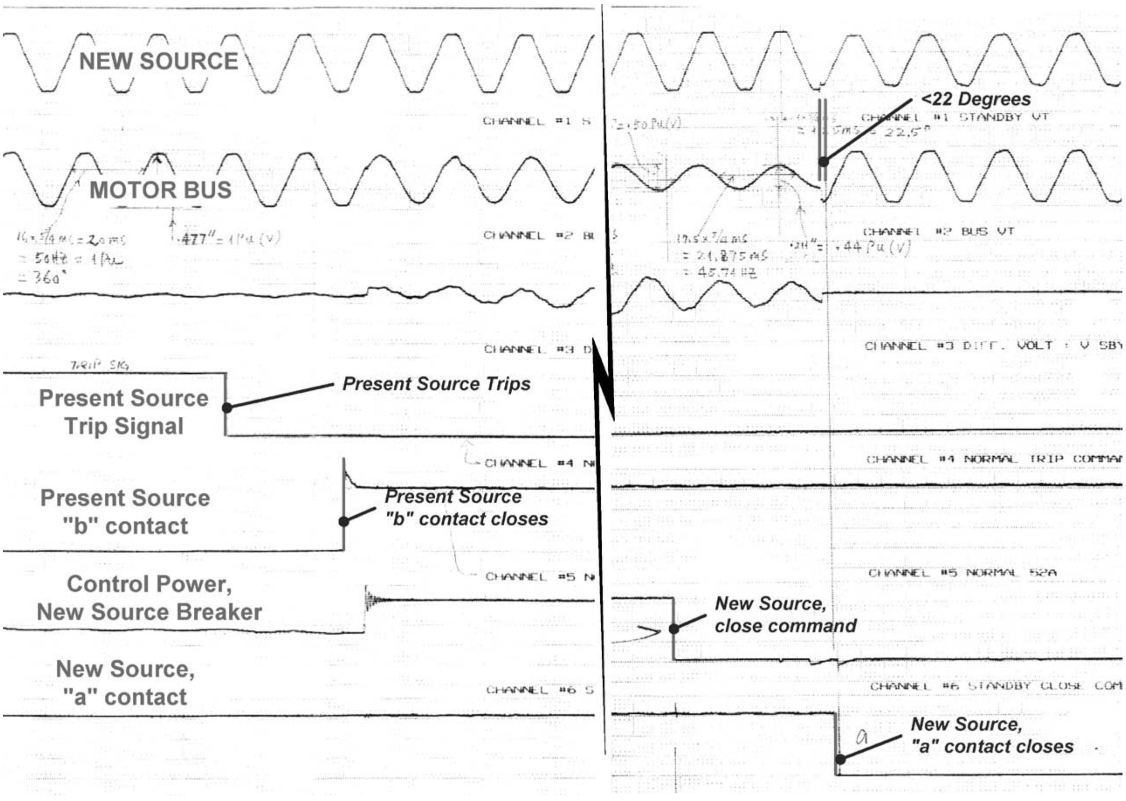

Fig. 12. Actual in-phase-transfer sequence.

supervisory fast-transfer sync check must be set so that it blocks before the phase angle becomes prohibitively large, and the angle setting must include the effect of the new-source breaker closing time.

4) The in-phase transfer should be initiated at an advance angle before the first-phase coincidence. The advance is calculated by an in-phase transfer specialized automatic synchronizing relay capable of predicting the angle based on the new-source breaker closing time and the rapidly increasing slip frequency.

5) The residual and long-time transfers only need to take into account that the motor-bus voltage has fallen to 0.25 pu or less. The new-source breaker closing time does not have to be considered, as the angle is now not important, as the resultant volts per hertz cannot exceed 1.33 V/Hz.

Fig. 8 is an actual ringdown of a motor bus and examines the fast-transfer scenario. The new source and motor-bus voltages (same phase) are shown. This oscillograph, and the oscillographs shown in Figs. 9–13, is from a 50-Hz system; however the observations and principles explored apply to any nominal frequency. Once the breaker is tripped, a delay of 2.5 cycles is given to allow the breaker to electrically interrupt the current flow, and then a high-speed sync check relay will either allow or block the transfer, based on its setting. Allowing 1.75 cycles for the new-source breaker to close, it can be graphically shown that the phase angle is 37°. Using (1), it can be demonstrated that for the 37° phase angle, with a 0.89-pu voltage remaining on the motor bus, that the 1.33-V/Hz limit would not be violated with this fast transfer. It should be noted that the breaker times used were provided by the plant, and that typical American National Standards Institute (ANSI) rated breakers have trip and close times of 4 cycles, respectively.

The next available transfer is the in-phase transfer. Fig. 9 is an actual ringdown of a motor bus and examines the in-phase transfer scenario. An in-phase transfer will be made if the motor-bus voltage stays above 0.25 pu, and the slip is not greater than the measurement limits of the specialized automatic synchronizing equipment, typically 5–10 Hz. With the breaker closing time as an input, the proper advance angle is calculated using an algorithm that takes into account the decay in motor-bus frequency, which is not linear. Depending on the inertia and the ability of the motors on the bus to hold up the voltage, this transfer may take place many hertz from the initial tripping of the present source.

The next available transfer is the residual and long-time transfers. Fig. 10 is an actual ringdown of a motor bus and examines the residual and long-time transfer scenarios. A residual transfer will be made if the motor-bus voltage falls below 0.25 pu, regardless of the slip frequency or phase angle. The long-time transfer can be made without a voltage input. It uses the ringdown results and a time that is longer than the expected duration of the motor-bus voltage remaining above 0.25 pu is assigned.

V. TRANSFER SEQUENCE ANALYSIS

A. Actual Transfers

Fig. 11 is an actual MBT and illustrates the fast-transfer scenario. The new source and motor-bus voltages (same phase) are shown. This oscillograph is from a 50 Hz system; however the principles apply to any nominal frequency. The transfer was sequential, using a high-speed sync check as a permissive after a short delay to assure that the present source was disconnected from the motor bus. The angle after the short delay was within the sync-check setting, so a transfer was allowed. The angle between the motor bus and the new source just prior to connection to the new source was 11°. With the voltage near rated and the phase angle of 11°, the 1.33 V/Hz level was not violated. Note how the voltage did not depress once the new source was connected, as the motors were still spinning. This transfer involved a motor bus with a large synchronous motor and smaller induction motors. The synchronous motor was connected to a high inertia load (fan). When examining a fast transfer, it can be seen that if the new-source voltage lags the present-source voltage, it can actually aid the transfer process by providing a longer time for the phase angle to increase to a level that would produce a violation of the 1.33-V/Hz limit. In addition to a timer to slightly delay the permissive of the sync check, a timer is used to block the fast transfer after an interval that would allow the phase angle to increase beyond an acceptable value. If the window for a fast transfer expires before the first slip cycle occurs, a sync check is not a satisfactory method for closure on the rapidly growing slip frequency between the motor bus in coastdown and the new source.

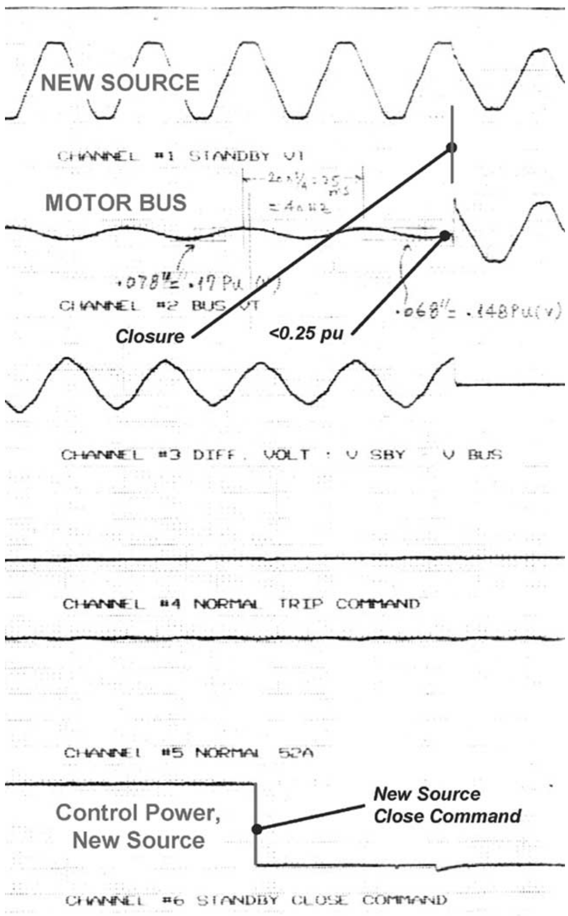

Fig. 13. Actual residual-transfer sequence.

Fig. 12 is an actual ringdown of a motor bus and illustrates the in-phase transfer scenario. The transfer was sequential, using a specialized automatic synchronizer to command the new-source breaker closure prior to the actual synchronous point between the motor bus and the new source. The angle between the motor bus and the new source just prior to connection to the new source was less than 22°. With the voltage at 0.5 pu and the phase angle of less than 22°, the 1.33-V/Hz level was not violated. Note how the voltage did not depress once the new source was connected as the motors were still spinning. This transfer involved a motor bus with large synchronous motors, and large and small induction motors. The in-phase transfer opportunity is limited by the ability of the equipment to perform the specialized automatic synchronization. Present state-of-the-art technology can affect the proper transfer with slip frequencies up to 10 Hz. If the slip frequency is larger than the maximum of the specialized automatic synchronizing equipment, the in-phase transfer is blocked. This is typically accomplished using a timer that examines the interval from the transfer initiation that will block the in-phase transfer so it cannot occur at too high of a slip frequency. Note a setting for the slip frequency does not have to be derived from inspection of a ringdown.

Fig. 13 is an actual ringdown of a motor bus and examines the residual and long-time transfer scenarios. Either of these transfers is made without regard to the phase angle between the motor bus undergoing coastdown and the new source. Note how there is a small voltage depression on the new source after connection to the motor bus as the motors have decelerated significantly, and the motors' stator windings undergo a current inrush at a value of less than the locked rotor.

VI. CONCLUSION

Several conclusions may be drawn by examining the ringdowns and actual transfers.

1) The fast transfer requires analysis of a ringdown or simulation to determine what the phase angle will be at the instant of connection to the new source. Worst case scenarios should be considered, which include changes in loading that include inertia and mixture of synchronous and induction machines.
2) The sync-check equipment to be used for supervising fast transfers must be able to detect a phase angle and block very rapidly if the angle moves outside of the desired range. Sync-check relays used for traditional applications may not have the required speed of operation to effectively block if required.
3) A sequential supervised transfer may be implemented to selectively allow or block the fast transfer under actual measured conditions. The supervised sequential transfer impacts the speed of the fast-transfer scheme by necessitating a small time delay to enable phase-angle measurements and to allow a block of the transfer to occur if determined necessary.
4) The in-phase transfer offers an opportunity to synchronize a motor bus on the first available slip cycle. This type of transfer will enable process continuity as the motors are still spinning and the residual voltage in the motor is still above 0.25 pu.
5) Specialized automatic synchronizing equipment is required for an in-phase transfer, which can determine the deceleration of the motor bus and affect a new-source breaker closure near phase coincidence.
6) Automatic synchronizing relays used for traditional generator and transmission synchronizing lack the ability to account for the rapid deceleration of the motor bus.
7) The residual and long-time transfers may interrupt the process. Load shedding may be necessary to restart the motors as the combined starting currents are high and may cause a voltage drop thereby overloading the bus.
8) Control logic that includes supervision of the breaker contacts and the application of supervisory timers is necessary to coordinate the possible transfer opportunities.

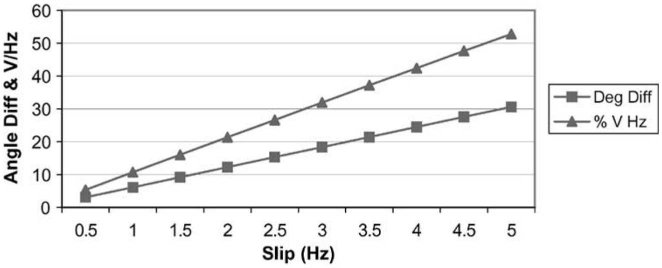

Fig. 14. Angle difference and volts per hertz versus slip at 1 pu.

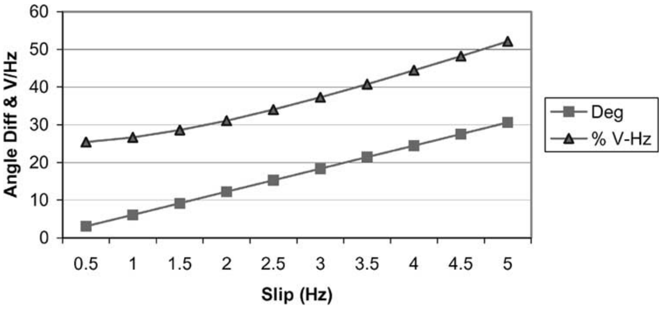

Fig. 15. Angle difference and volts per hertz versus slip at 0.75 pu.

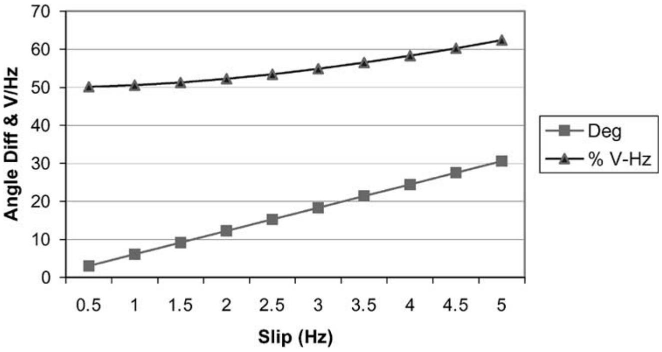

Fig. 16. Angle difference and volts per hertz versus slip at 0.50 pu.

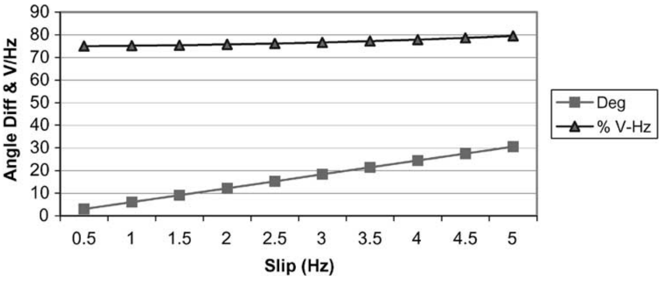

Fig. 17. Angle difference and volts per hertz versus slip at 0.25 pu.

APPENDIX

This appendix explores the effect of nonrepeatability of circuit-breaker closing times and its effect on the predicted breaker closing angular error, and the angular error's effect on the resultant volts per hertz on motor buses.

Figs. 14–17 plot the angular difference and volts per hertz versus slip at various per unit motor-bus voltages. This indicates that excessive volts per hertz, designated as greater than

TABLE I

RESULTANT VOLTS PER HERTZ AT VARIOUS LEVELS OF DECAYING MOTOR-BUS VOLTAGE, SLIP FREQUENCY, AND ANGULAR ERROR

			mS (Th)	mS(Err)								
Slip	Es	Em	CB Time	CB Time	Deg (Th)	Deg (Err)	Deg Diff	Deg-Rad	Cos Rad	Eq	Sqroot	% V Hz
0.5	1	1	67	84	12.06	15.12	3.06	0.05341	0.99857	0.003	0.053	5
1	1	1	67	84	24.12	30.24	6.12	0.10681	0.9943	0.011	0.107	11
1.5	1	1	67	84	36.18	45.36	9.18	0.16022	0.98719	0.026	0.160	16
2	1	1	67	84	48.24	60.48	12.24	0.21363	0.97727	0.045	0.213	21
2.5	1	1	67	84	60.3	75.6	15.3	0.26704	0.96456	0.071	0.266	27
3	1	1	67	84	72.36	90.72	18.36	0.32044	0.9491	0.102	0.319	32
3.5	1	1	67	84	84.42	105.84	21.42	0.37385	0.93093	0.138	0.372	37
4	1	1	67	84	96.48	120.96	24.48	0.42726	0.91011	0.180	0.424	42
4.5	1	1	67	84	108.54	136.08	27.54	0.48066	0.88669	0.227	0.476	48
5	1	1	67	84	120.6	151.2	30.6	0.53407	0.86074	0.279	0.528	53
Slip	Es	Em	CB Time	CB Time	Deg (Th)	Deg (Err)	Deg	Deg-Rad	Cos Rad	Eq	Sqroot	% V-Hz
0.5	1	0.75	67	84	12.06	15.12	3.06	0.05341	0.99857	0.065	0.254	25
1	1	0.75	67	84	24.12	30.24	6.12	0.10681	0.9943	0.071	0.267	27
1.5	1	0.75	67	84	36.18	45.36	9.18	0.16022	0.98719	0.082	0.286	29
2	1	0.75	67	84	48.24	60.48	12.24	0.21363	0.97727	0.097	0.311	31
2.5	1	0.75	67	84	60.3	75.6	15.3	0.26704	0.96456	0.116	0.340	34
3	1	0.75	67	84	72.36	90.72	18.36	0.32044	0.9491	0.139	0.373	37
3.5	1	0.75	67	84	84.42	105.84	21.42	0.37385	0.93093	0.166	0.408	41
4	1	0.75	67	84	96.48	120.96	24.48	0.42726	0.91011	0.197	0.444	44
4.5	1	0.75	67	84	108.54	136.08	27.54	0.48066	0.88669	0.232	0.482	48
5	1	0.75	67	84	120.6	151.2	30.6	0.53407	0.86074	0.271	0.521	52
Slip	Es	Em	CB Time	CB Time	Deg (Th)	Deg (Err)	Deg	Deg-Rad	Cos Rad	Eq	Sqroot	% V-Hz
0.5	1	0.5	67	84	12.06	15.12	3.06	0.05341	0.99857	0.251	0.501	50
1	1	0.5	67	84	24.12	30.24	6.12	0.10681	0.9943	0.256	0.506	51
1.5	1	0.5	67	84	36.18	45.36	9.18	0.16022	0.98719	0.263	0.513	51
2	1	0.5	67	84	48.24	60.48	12.24	0.21363	0.97727	0.273	0.522	52
2.5	1	0.5	67	84	60.3	75.6	15.3	0.26704	0.96456	0.285	0.534	53
3	1	0.5	67	84	72.36	90.72	18.36	0.32044	0.9491	0.301	0.549	55
3.5	1	0.5	67	84	84.42	105.84	21.42	0.37385	0.93093	0.319	0.565	56
4	1	0.5	67	84	96.48	120.96	24.48	0.42726	0.91011	0.340	0.583	58
4.5	1	0.5	67	84	108.54	136.08	27.54	0.48066	0.88669	0.363	0.603	60
5	1	0.5	67	84	120.6	151.2	30.6	0.53407	0.86074	0.389	0.624	62
Slip	Es	Em	CB Time	CB Time	Deg (Th)	Deg (Err)	Deg	Deg-Rad	Cos Rad	Eq	Sqroot	% V-Hz
0.5	1	0.25	67	84	12.06	15.12	3.06	0.05341	0.99857	0.563	0.750	75
1	1	0.25	67	84	24.12	30.24	6.12	0.10681	0.9943	0.565	0.752	75
1.5	1	0.25	67	84	36.18	45.36	9.18	0.16022	0.98719	0.569	0.754	75
2	1	0.25	67	84	48.24	60.48	12.24	0.21363	0.97727	0.574	0.758	76
2.5	1	0.25	67	84	60.3	75.6	15.3	0.26704	0.96456	0.580	0.762	76
3	1	0.25	67	84	72.36	90.72	18.36	0.32044	0.9491	0.588	0.767	77
3.5	1	0.25	67	84	84.42	105.84	21.42	0.37385	0.93093	0.597	0.773	77
4	1	0.25	67	84	96.48	120.96	24.48	0.42726	0.91011	0.607	0.779	78
4.5	1	0.25	67	84	108.54	136.08	27.54	0.48066	0.88669	0.619	0.787	79
5	1	0.25	67	84	120.6	151.2	30.6	0.53407	0.86074	0.632	0.795	80

1.33 pu, will not be created from a 1-cycle variance in the closing time of a 4-cycle circuit breaker.

The spreadsheets (see Table I) calculate the resultant volts per hertz at various levels of decaying motor-bus voltage, slip frequency, and angular error. The columns are designated as follows.

Slip	Slip frequency expressed in hertz.
Es	New-source voltage (pu).
Em	Motor-bus voltage (pu).
CB Time, mS (Th)	Four-cycle-breaker closing time.
CB Time, mS(Err)	Four-cycle-breaker with one cycle added.
Deg(Th)	Predicted advance angle to close breaker in degrees, using $[\angle = 360^{*}\Delta f^{*}T_{\mathrm{CB}}]$, where $\Delta f =$ slip frequency (Hz) and $T_{\mathrm{CB}} =$ circuit breaker closing time (mS).
Deg(Err)	Predicted advance angle to close breaker in degrees, using $[\angle = 360^{*}\Delta f^{*}T_{\mathrm{CB}}]$, where $\Delta f =$ slip frequency (Hz) and $T_{\mathrm{CB}} =$ circuit breaker closing time (mS).
Deg Diff	Angular difference between Deg(Th) and Deg(Err).
Deg-Rad	Conversion of degrees into radians for Excel's use.
Cos-Rad	Cosine of angle.
Eq	Law of Cosine equation applied without taking square root, $E_{\mathrm{r}}^2 = E_{\mathrm{s}}^2 + E_{\mathrm{m}}^2 - 2E_{\mathrm{s}}E_{\mathrm{m}}\cos\theta$.
Sqroot	Square root of Eq above, $E_{\mathrm{r}}(\mathrm{pu}) = \sqrt{E_{\mathrm{r}}^2}$.
V/Hz	percent V/Hz $= E_{\mathrm{r}}(\mathrm{pu})^{*}100$.

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