# Implementation of a Microprocessor-Based Motor Bus Transfer Scheme

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# IMPLEMENTATION OF A MICROPROCESSOR-BASED MOTOR BUS TRANSFER SCHEME



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***Abstract*****—**Critical process loads need to be safeguarded against power system disturbances and erroneous operations caused by human factors. During such events, a fast synchronism-supervised transfer scheme is required to ensure continuous operation. This paper discusses the implementation of a fast motor bus transfer scheme using existing protective relays. The scheme is designed to respond to local and remote (upstream) events in the substation. This makes possible an attempt to initiate a fast transfer for events that are remote to the motor bus. On a failure to achieve a fast transfer, the scheme resorts to an in-phase transfer and, if that fails, finally a residual transfer. Real-time dynamic modeling was performed to simulate motor bus decay and reacceleration. This paper provides the results of the simulations and the response of the transfer scheme.

*Index Terms*—Fast motor bus transfer, in-phase and residual transfer, reacceleration, real-time dynamic modeling.

## I. INTRODUCTION

While the bulk electric power system, defined by the North American Electric Reliability Corporation (NERC) as any system that is 100 kV and above, experiences availability of greater than 97 percent for ac circuits and greater than 98 percent for ac transformers, what is not captured by the NERC data is the impact that even a momentary interruption can have on an industrial process [1]. Those availability figures do not include equipment outages of equipment below 200 kV, whether owned by the utility or the industrial facility. The need to ride through interruptions and quickly and safely transfer critical process loads to an alternate source is extremely important for the safety and reliability of an entire process.

This paper outlines the implementation of a motor bus transfer (MBT) control scheme for a 4.16 kV bus in switchgear at a refinery in the United States. The refinery receives and delivers crude oil and finished product through a pipeline or from marine docks. The refinery has a total throughput capacity of 270,000 barrels per day. It produces a wide range of petroleum products, including gasoline, kerosene, diesel fuel, No. 2 and No. 6 fuel oils, heating oil, liquefied petroleum gases (LPGs), and petroleum coke.

## II. MOTOR BUS TRANSFER OVERVIEW

Before discussing details regarding how MBT was implemented at this particular location, a brief overview of MBT is warranted. The concept of MBT has been around for over 50 years [2]. The concepts and terminology used to describe MBT have been defined by several standards organizations [3] [4] [5]. The main challenge of any MBT system is to avoid closing the alternate source back onto the motor when the residual motor voltage is out of phase with the source.

Any time a motor is disconnected from its source, the voltage on the stator terminals does not immediately go to zero upon the opening of the source breaker. Rather, the motor voltage exhibits a decay in magnitude and in frequency. This is true of synchronous machines and induction machines. Induction machines rely on reactive power from the source for the current in their rotor circuit, and there is some amount of current trapped in the rotor bars following a disconnection of the source. The losses in the rotor circuit will cause the rotor current, and hence the flux and stator voltage, to decay.

Fig. 1 shows the characteristic rundown of a single machine. Note the decay in voltage magnitude and frequency. It is important to note that the frequency decay is not linear.

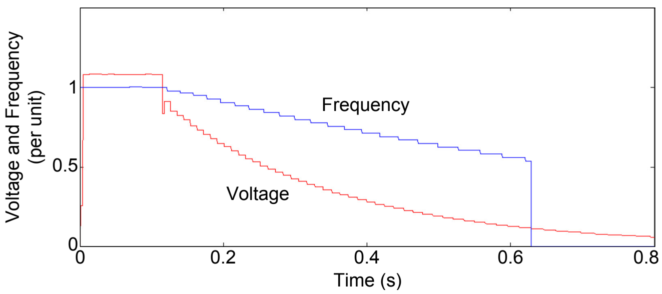


Fig. 1 Rundown Plot of Voltage Magnitude and Frequency Versus Time

Fig. 2 shows the phase angle between the motor bus voltage and the source voltage for the same rundown condition.

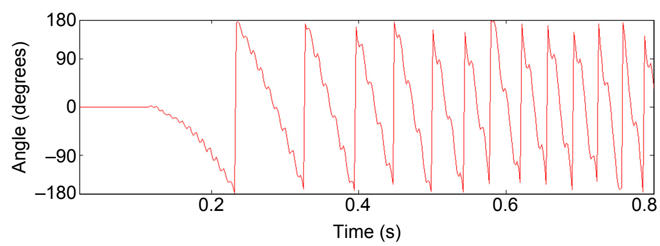


Fig. 2 Rundown Plot of Motor Bus Voltage Angle Versus Time

If the alternate source is connected before this residual voltage decays to a very small level, then a transient torque will result. The amount of electrical torque generated depends on the magnitude and phase angle of both the source voltage and the motor bus voltage. An illustrative, simplified equation that relates the peak electrical torque to the voltage magnitudes and angle of the source voltage and the motor voltage is given in (1) [6].

$$T_e = \frac{E^2}{x} \bullet \sin(\delta) + 2\sin\left(\frac{\delta}{2}\right) \tag{1}$$

where:

*E* is the magnitude of the source voltage and the motor bus voltage.

*x* is the total equivalent reactance in the system and the motor.

$\delta$ is the phase angle between the source voltage and the motor bus voltage.

Equation (1) makes some very broad assumptions, namely that the voltage magnitude and frequency of the source and motor bus remain near their rated values during the interruption. These assumptions are not valid for any real transfer, but they allow us to generate simple plots, such as the one shown in Fig. 2. Fifty years ago, when (1) was published in [6], the data on machines and the simulating capability available today were not yet in existence.

In Fig. 3, notice that the peak torque occurs when the angle of closure is near 120 degrees. The per-unit torque observed is much lower than would be expected when actually closing into a motor when it is 120 degrees out of phase with the source, with some references noting peak electrical torques of greater than 10 per unit [7]. But Fig. 3 and (1) do illustrate two important points. First, the peak electrical torque does not occur when the close occurs at the point the motor bus voltage and the source voltage are 180 degrees out of phase. Second, simplified equations do not yield reasonable results when attempting to estimate electrical torque.

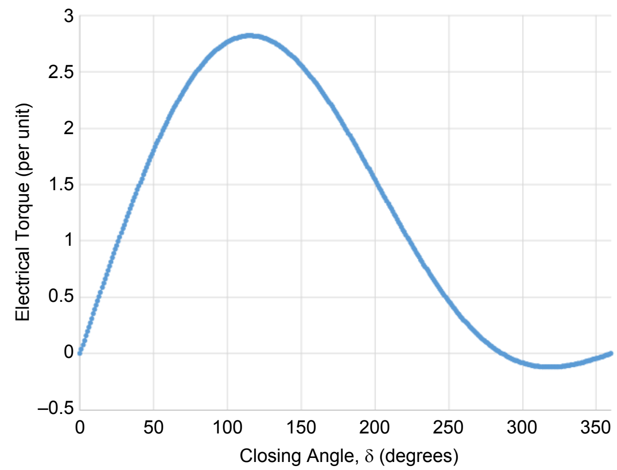


Fig. 3 Electrical Torque Versus Closing Angle in Degrees

While there are no strict published limits on motor torque, [3] does offer some torque limits related to smaller induction machines. The existing guideline for a safe transfer is based not on torque but rather on a resultant V/Hz calculation, given in (2) [3] [4]. Essentially, the resultant V/Hz as calculated in (2) should be less than 1.33 per unit at the time of transfer.

$$E_R = \sqrt{E_S^2 + E_M^2 - 2 \bullet E_S \bullet E_M \bullet \cos(\delta)} \tag{2}$$

where:

$E_S$ is the per unit V/Hz of the alternate source.

$E_M$ is the per unit V/Hz of the motor bus.

$\delta$ is the phase angle between the source voltage and the motor bus voltage.

While this is still the only limit defined by standards for the criteria for a successful transfer, there is documentation that suggests that this criterion does not adequately address limiting damaging transient torques on the machine [7] [8]. In addition, there are several references that note the important difference between the electrical torque (i.e., torque transmitted across the air gap of a machine) and the actual torque on the shaft system of a motor [8]. Because of these issues with the use of simple formulas and criteria, often a computer simulation of the electrical power system and mechanical system of the motor is warranted. This simulation is typically a time-domain transient model of the electrical power system and mechanical system coupled to the motor.

Note that no matter what criteria are used and whether the electrical torque is calculated or a more sophisticated method is used to estimate the electrical or shaft torque based on simulation, the basic goals of any MBT method are the following:

1. Avoid closing into the alternate source when the motor bus voltage and the alternate source voltage are out of phase.
2. Limit the transient torque on the motor as much as possible, while still maintaining the availability of the process by riding through momentary transfer interruptions and reducing the occurrence of a sustained and unwanted interruption.

How is this accomplished? Standards and experience have outlined several methods. This paper focuses on sequential transfers, where the primary source breaker opens before closing the alternate source breaker, because this is the type of transfer that was selected for the refinery project. Among sequential transfers, there are three methods: fast transfer, in-phase transfer, and residual transfer.

### *A. Fast Transfer*

In concept, the fast transfer method attempts to close the alternate source breaker as soon as possible following the opening of the primary source. If this is done quickly enough, the motor bus voltage and the alternate source voltage will still be in phase, or close to in phase, with one another. Several factors may complicate a fast transfer by causing the alternate source voltage and motor bus voltage to be out of phase prior to the transfer. Once the source breaker opens, the motor bus will start to move farther away in phase angle from the alternate source voltage. The most commonly cited example of a transfer-initiating event is an upstream fault on a primary source. For these cases, many engineers familiar with MBT suggest using a supervised fast transfer [5]. This involves supervising the fast transfer with a synchronism-check relay to verify that the motor bus voltage and alternate source voltage are in phase just before closing the alternate source breaker. The synchronism-check relay must be fast enough to block a transfer if the motor bus voltage and alternate source voltage are not in phase.

The benefit of the fast transfer is that it provides the shortest interruption time of any of the three methods. The downside is that the conditions that initiate a motor bus transfer may cause the phase angle between the alternate source and motor bus to be too far apart to allow a supervised fast transfer to occur. The use of unsupervised fast transfers is discouraged.

### *B. In-Phase Transfer*

The in-phase transfer method attempts to close the breaker when the alternate source voltage and motor bus voltage are in phase again, typically after one or two slip cycles. The device that controls an in-phase transfer must know the breaker closing time accurately and be able to predict what the phase angle will be when the breaker actually closes. In Fig. 2, it can be seen that after a delay, the voltage angle between the motor bus and alternate source bus returns to 0 degrees. The intelligent electronic device (IED) controlling the in-phase transfer must also be able to block an in-phase transfer if the rate of change of slip is too high between the two sources.

### *C. Residual Transfer*

Finally, the residual transfer method simply waits for the motor bus voltage to decay to a small value, which is typically less than 0.3 or 0.25 per unit. While there are some concerns that the relay or IED controlling a residual transfer must be able to accurately measure the residual bus voltage magnitude [9], modern IEDs are generally capable of accurately measuring waveforms of decaying magnitude and frequency seen in MBT and other applications, such as generator protection [10].

Residual transfers have the advantage of being the simplest to use in terms of protective relaying and the device performing the transfer logic. However, the scheme may suffer because, in many cases, by the time the motor bus voltage decays to below 0.3 per unit, the process may already be stopped. Generally, a combination of the three transfer methods (fast, in-phase, and residual) is commonly applied.

## III. IMPLEMENTATION

The refinery transfer scheme was implemented on a 4.16 kV switchgear, as shown in Fig. 4. The scheme uses two MBT IEDs (IED-MBT-A and IED-MBT-B), which provide the control logic for automatic and manual transfers for the three-breaker motor bus configuration as well as standard feeder protection functions. The scheme initiates simultaneous fast transfers upon the opening of specified breakers or an upstream feeder protective trip signal. The scheme also provides synchronized and supervised fast, in-phase, and residual transfers based on the opening of a main breaker.

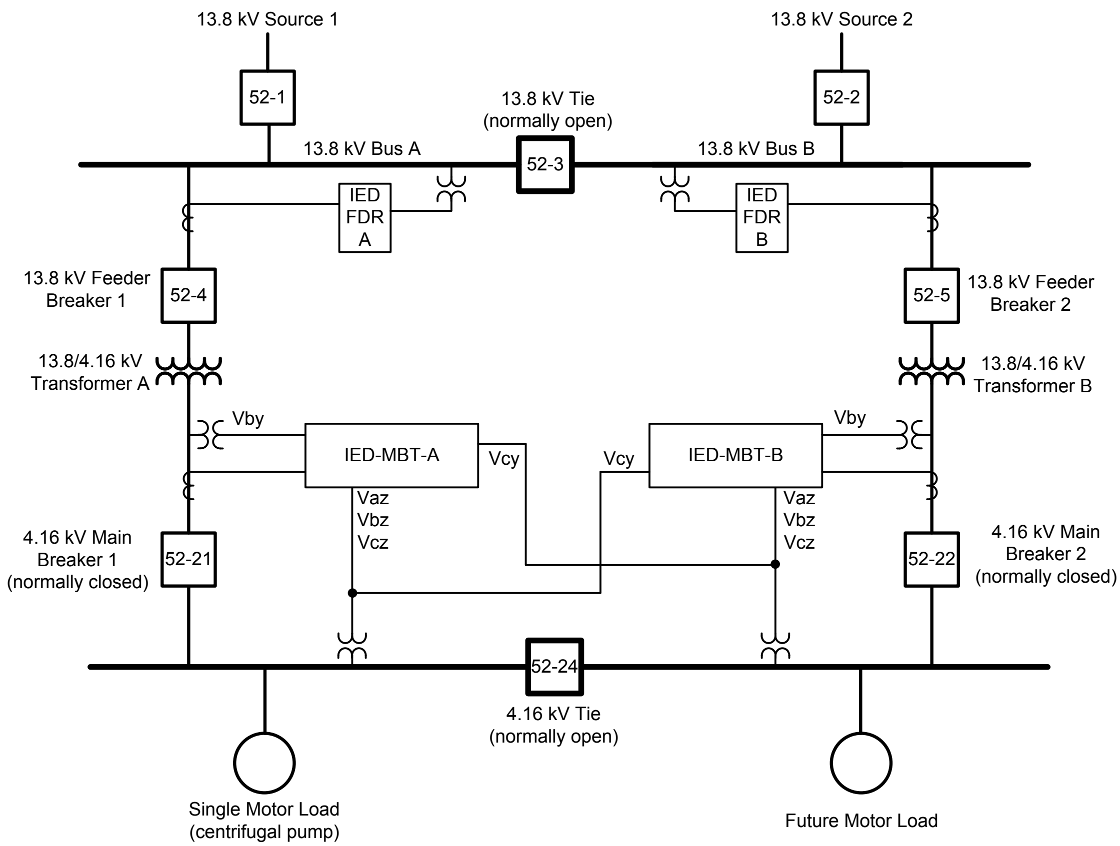


Fig. 4 Refinery MBT Scheme Overview

The breaker statuses of 52-1, 52-2, 52-3, 52-4, and 52-5 are sent via the IEC 61850 GOOSE protocol to the MBT IEDs for initiating the MBT process. In addition to the breaker statuses, the upstream relays send protective trip and loss of power flow signals to initiate transfers. A detailed transfer algorithm, shown in Fig. 5, is programmed in the MBT IEDs.

Manual and automatic operations can be performed using the front-panel pushbuttons on the MBT IEDs but only if certain voltage requirements are met. In manual mode, to close the main breakers, the source voltage must be healthy and the bus voltage must either be dead or synchronized with the source voltage. To close the tie breaker, one of the bus voltages must be live and the other dead or they must both be live and synchronized. Voltage supervision is not required to open the breakers. During manual operation, automatic mode is disabled in the MBT IEDs to prevent undesired transfers caused by a breaker opening or an external initiation. The transfer from a normal operating configuration to a one-source configuration is caused by the opening of one of the main breakers. To return to the normal operating configuration, a manual closed or open transition transfer can be performed.

An automatic transfer can be externally initiated by upstream conditions or locally initiated by opening main breaker 52-21 or 52-22.

The following four cases each attempt a simultaneous fast transfer where the open and close signals are sent at the same time, causing the least amount of motor voltage disturbance:

1. Upstream 13.8 kV bus breakers initiate a transfer if one of the main breakers and the tie breaker (52-1 or 52-2 and 52-3) are open at the same time.
2. The opening of the upstream 13.8 kV feeder breakers (52-4 or 52-5) initiates a transfer.
3. A protective trip signal from the upstream feeder relays initiates transfer if the local MBT IED does not detect a fault.
4. A protective trip signal from the upstream transformer relays initiates transfer if the local MBT IED does not detect a fault.

If a loss of power signal is sent from the upstream feeder breaker, fast transfer mode will be disabled and an in-phase transfer will be attempted with a subsequent residual transfer if the in-phase transfer is unsuccessful.

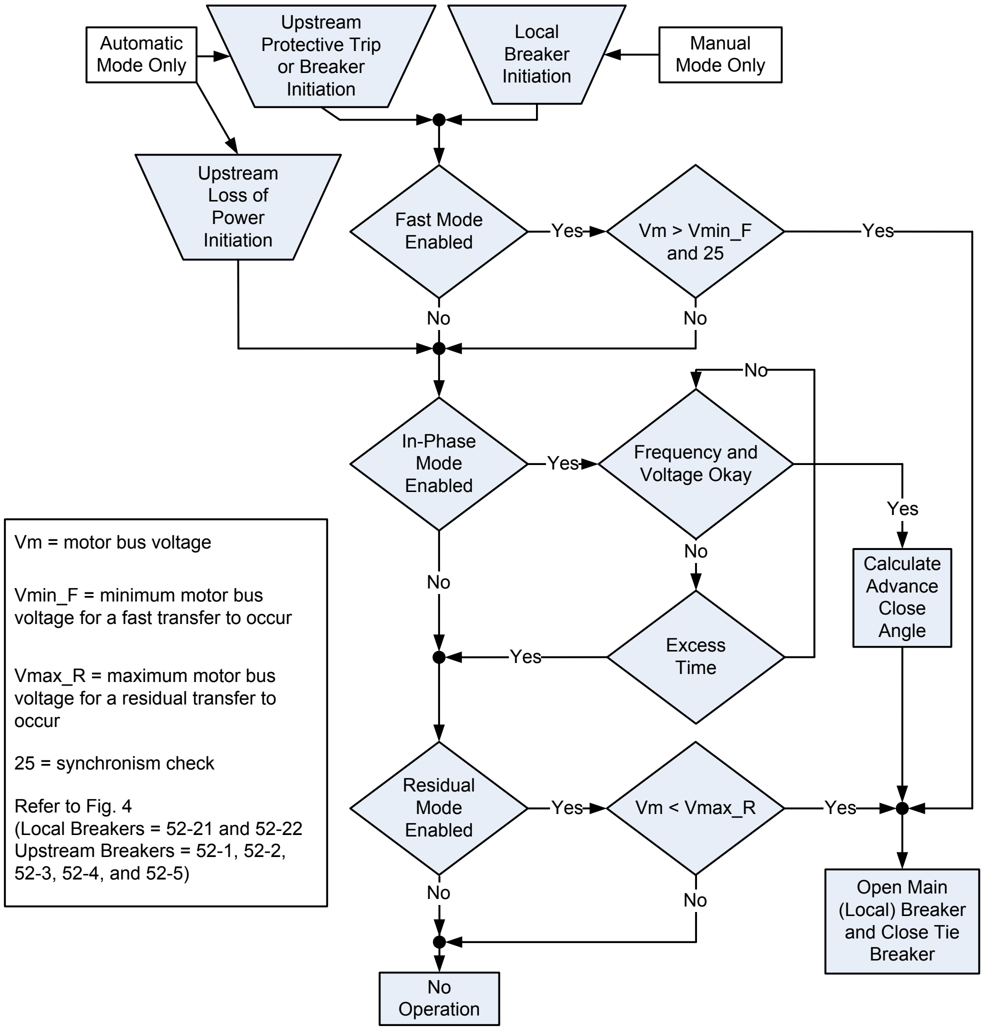


Fig. 5 Motor Bus Transfer Algorithm

## IV. MODELING

Modeling of an 800 hp induction motor was performed using real-time digital dynamic modeling software. The model used a star-connected stator winding and a shorted rotor winding. The input parameters to the model were obtained from motor data sheets, which included the parameters of Steinmetz's equivalent circuit [11]. The machine parameters used in the model are shown in Table I.

Load torque ($T_L$) was given as a run-time input to the model. The load torque is characterized by the initial breakaway torque (L) and the final value (F) [11], as shown in (3).

$$T_L = L(1-w)^5 + Fw^2 \tag{3}$$

where *w* is the speed in per unit, and the values for *L* and *F* are obtained from the manufacturer-provided motor curves.

TABLE I
MACHINE PARAMETERS

| | Value | |
|---|---|---|
| **Rated Voltage (V)** | 4,000 | |
| **Rated Speed (rpm)** | 1,792 | |
| **Rated Power (hp)** | 800 | |
| **Rotor Inertia (lb-ft$^2$)** | 466 | |
| **Load Inertia (lb-ft$^2$)** | 45 | |
| | **Full Load** | **Locked Rotor** |
| **R1 (per unit)** | 0.00585 | 0.00473 |
| **X1 (per unit)** | 0.07873 | 0.07602 |
| **R2 (per unit)** | 0.00379 | 0.01630 |
| **X2 (per unit)** | 0.12438 | 0.04944 |
| **XM (per unit)** | 2.91607 | 2.59826 |

The system modeled was a single motor load connected to a 4.16 kV motor bus, which was fed from one of the two available sources—the main source or the alternate source. The objective of the modeling effort was to assess the electrical torques developed at the motor during the transfer process. In addition to this, the performance of the MBT IED for the in-phase transfer simulations was validated. Simulations involving various transfer scenarios were played back to the MBT IED as COMTRADE files using secondary injection test sets. The MBT IED test validated that the device correctly tracked the slip, voltage, rate of change of voltage, and rate of change of slip and correctly blocked or allowed transfer when the user-defined limits were exceeded. The MBT IED test also validated that the close command and breaker close were correctly performed at a minimal phase angle difference.

Model validation against the motor data was performed. A motor rundown test determined the voltage decay rate. This voltage decay rate is referred to as the open circuit time constant and can be determined from the equivalent circuit parameters. Equation (4) is used to calculate this time constant [8].

$$T_{d0} = (XM + X2) / (2 \cdot \pi \cdot f \cdot R2) \tag{4}$$

where $f$ is the system frequency.

It is interesting to note that (4) is based on the assumptions that the motor speed remains constant during the time that the motor is disconnected and also that the rotor resistance (R2) is a constant. This is not the case for an actual rundown test. Fig. 6 shows the variation between the decay voltage for a simulated rundown using variable motor speed and rotor resistance versus the simulated case where the motor speed and the rotor resistance is constant. Fig. 6 also shows the rundown curve from the motor data sheet. Note that the model closely matches the voltage curve from the data sheet when the rundown simulation uses a constant speed and rotor resistance. The purpose of this model is not to match the calculated curve from the data sheet but rather to predict the real-world reaction of the motor to a loss of source and subsequent transfer operation. With this in mind, the simulated transfers were all performed with the variable motor speed and rotor resistance.

Fig. 7 shows a comparison of the electrical torque from the simulation and the torque in the motor data sheet. The initial slip for these simulations was considered to be 1 per unit, such as with a stationary motor shaft.

Fig. 8 shows the motor starting current obtained from the simulation versus the data sheet values.

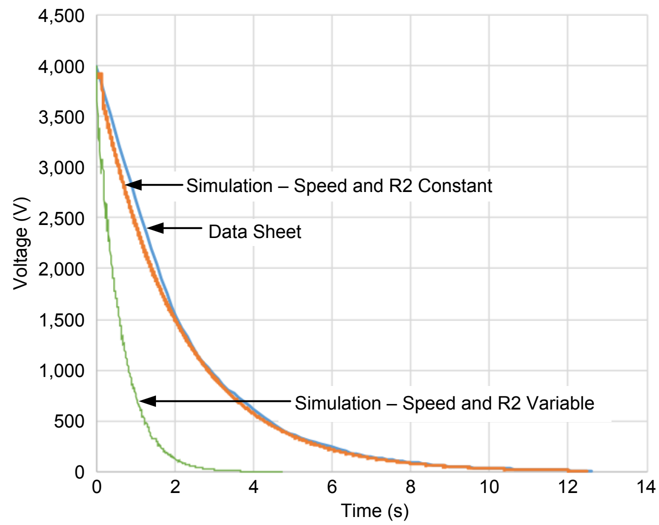


Fig. 6 Voltage Decay Validation

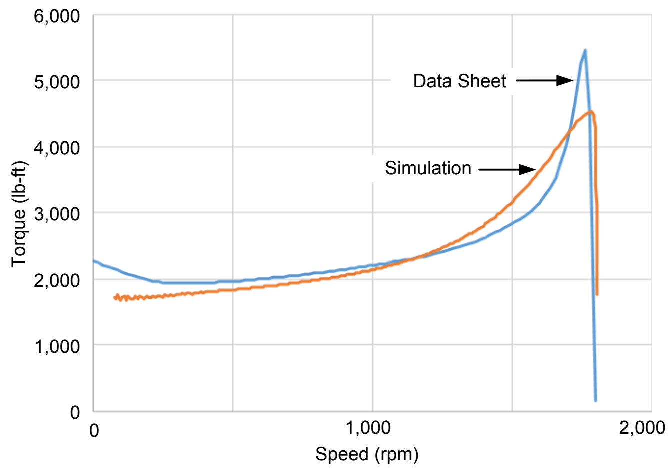


Fig. 7 Motor Torque Comparison

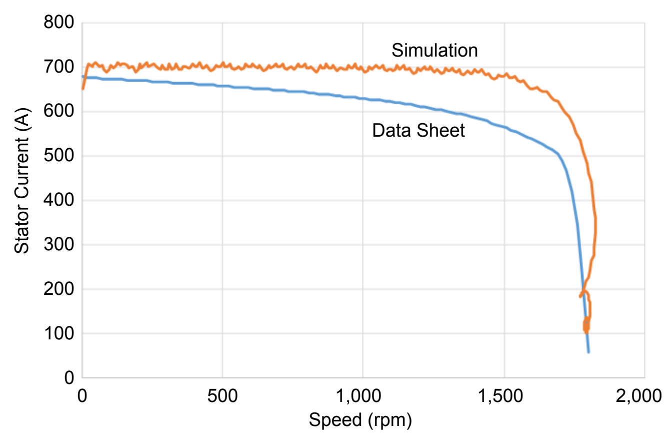


Fig. 8 Motor Starting Current Comparison

## A. *Test Case I: Fast Transfer*

The sequential fast transfer simulation was performed by opening the present source breaker and immediately closing the transfer source breaker. Fig. 9 presents the MBT IED event report obtained during an attempted fast transfer. As shown, the fast transfer was blocked, resulting in a subsequent in-phase transfer. The fast transfer supervision digital bit dropped out due to the synchronism check detecting a slip rate higher than the setting.

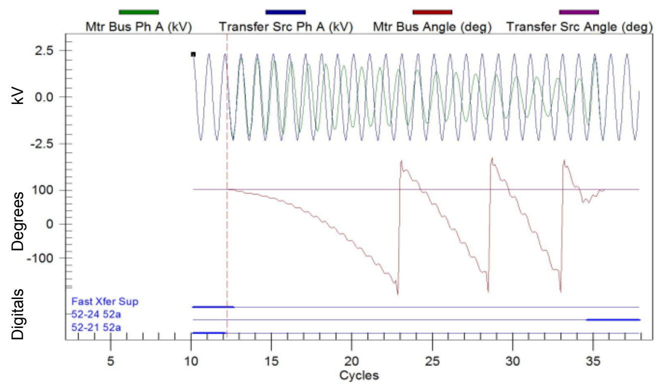


Fig. 9 Relay Test Results for an In-Phase Transfer

Fig. 10 is the resulting electrical torque during an unsupervised fast transfer operation. By blocking the transfer, as in Fig. 9, the high electrical torque the motor experienced for an unsupervised transfer is avoided. For the simulated conditions, a fast transfer is not achievable.

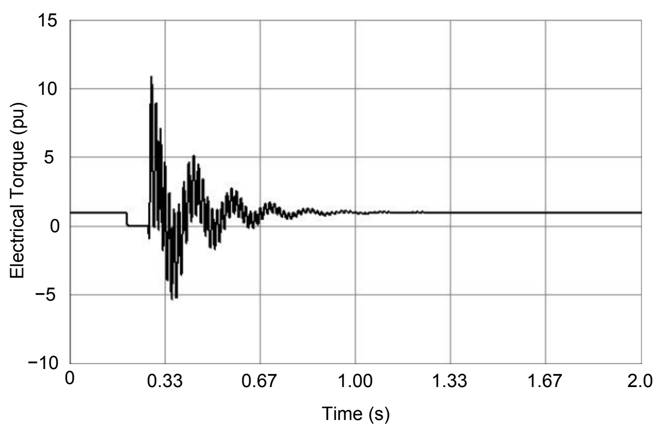


Fig. 10 Simulation Results for an Unsupervised Fast Transfer

## B. *Test Case II: In-Phase Transfer*

The in-phase transfer simulation was performed by disconnecting the source to the motor running at rated speed. For the duration of this test, the fast transfer mode was disabled. When both source breakers were open and the motor bus voltage was decaying in magnitude and frequency, the MBT IED calculated the minimum approaching phase angle difference between the transfer source voltage and the decaying motor bus voltage. When the IED determined that the conditions for attempting an in-phase transfer were present, it issued a close command based on the breaker closing time. Fig. 11 shows the voltage waveforms and the electrical torque that developed during the transfer. The in-phase transfer occurred in about 22.5 cycles. The test results show that the relay correctly determined the time to transfer and closed at a minimal angle between the voltage signals. This relay test is shown in Fig. 9, and a closer view of the close angle is shown in Fig. 12.

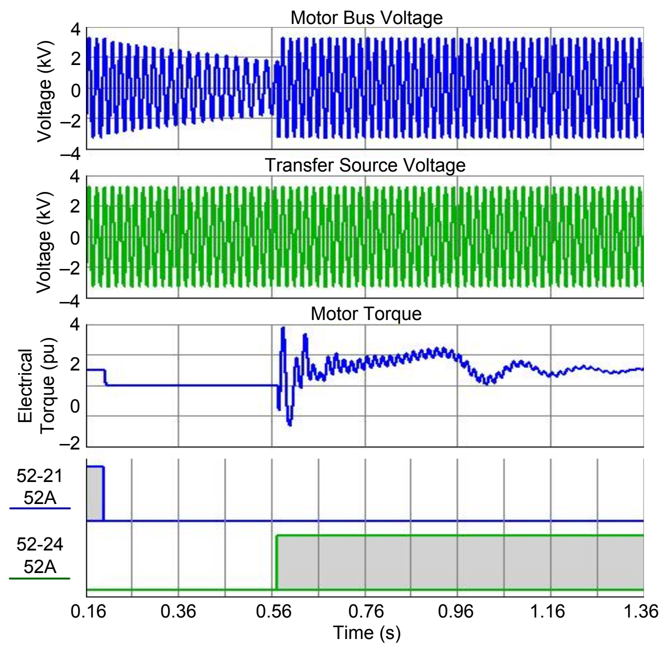


Fig. 11 Simulation Results for an In-Phase Transfer (Zoomed)

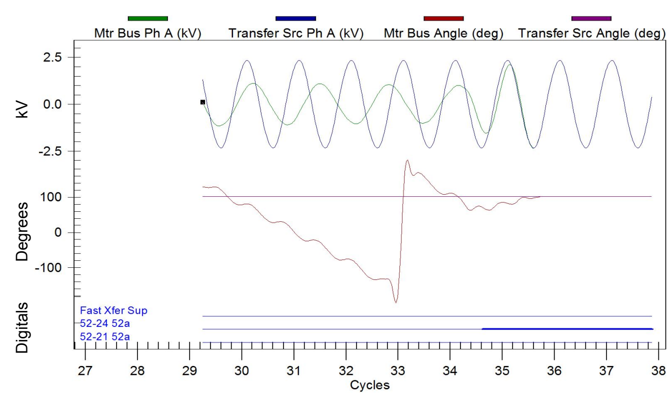


Fig. 12 Relay Test Results for an In-Phase Transfer (Zoomed)

## C. Test Case III: Residual Transfer

In this simulation, the motor bus voltage decayed significantly so that closing the transfer source breaker would not cause any damage to the machine. The torque produced for a residual transfer, as shown in Fig. 13, was very similar to the torque produced during a motor start. The total time for a residual transfer was about 66.625 cycles. Fig. 13 shows the waveforms for a residual transfer.

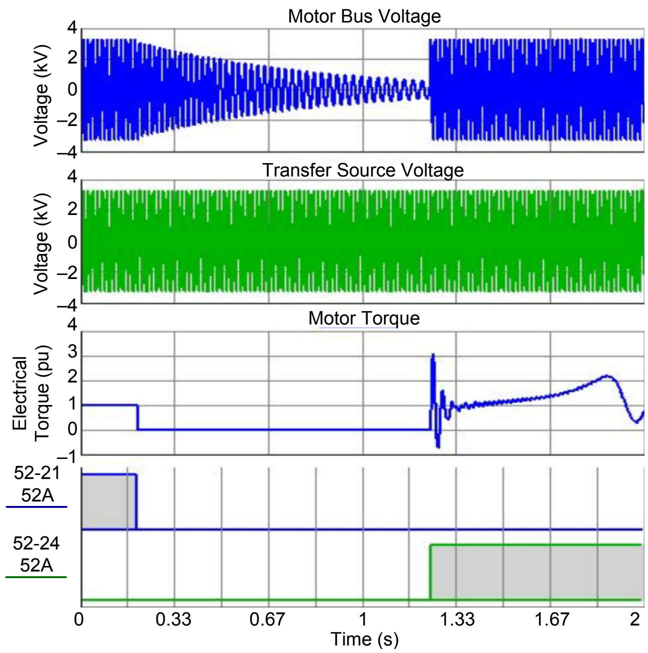


Fig. 13 Simulation Results for a Residual Transfer

# V. CONCLUSIONS

This paper reviewed the application and basic concepts of a motor bus transfer system in a refinery to improve the availability of the process, including an overview of the methods of transfer. Some key lessons learned include the following:

1. The implementation of a motor bus transfer scheme improves process availability without damaging the motor loads.
2. Performing dynamic simulation is valuable and important.
3. The machine model needs to be validated against the manufacturer data.
4. There is value in testing the relay algorithm with the simulated results.
5. Synchronism-check supervision for fast transfer is recommended to prevent out-of-phase closing and avoid high transient torque.

Ideally, the simulation results should be compared against the actual rundown or transfer events. At the time of the publication of this paper, the transfer scheme was in service for over one year with no transfer events. Because of the critical nature of the loads, it is not feasible to perform staged rundown tests. Efforts are ongoing to gather real-world data.

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# VII. VITAE

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