MOTOR BUS TRANSFER APPLICATIONS ISSUES AND CONSIDERATIONS

Tom Branch

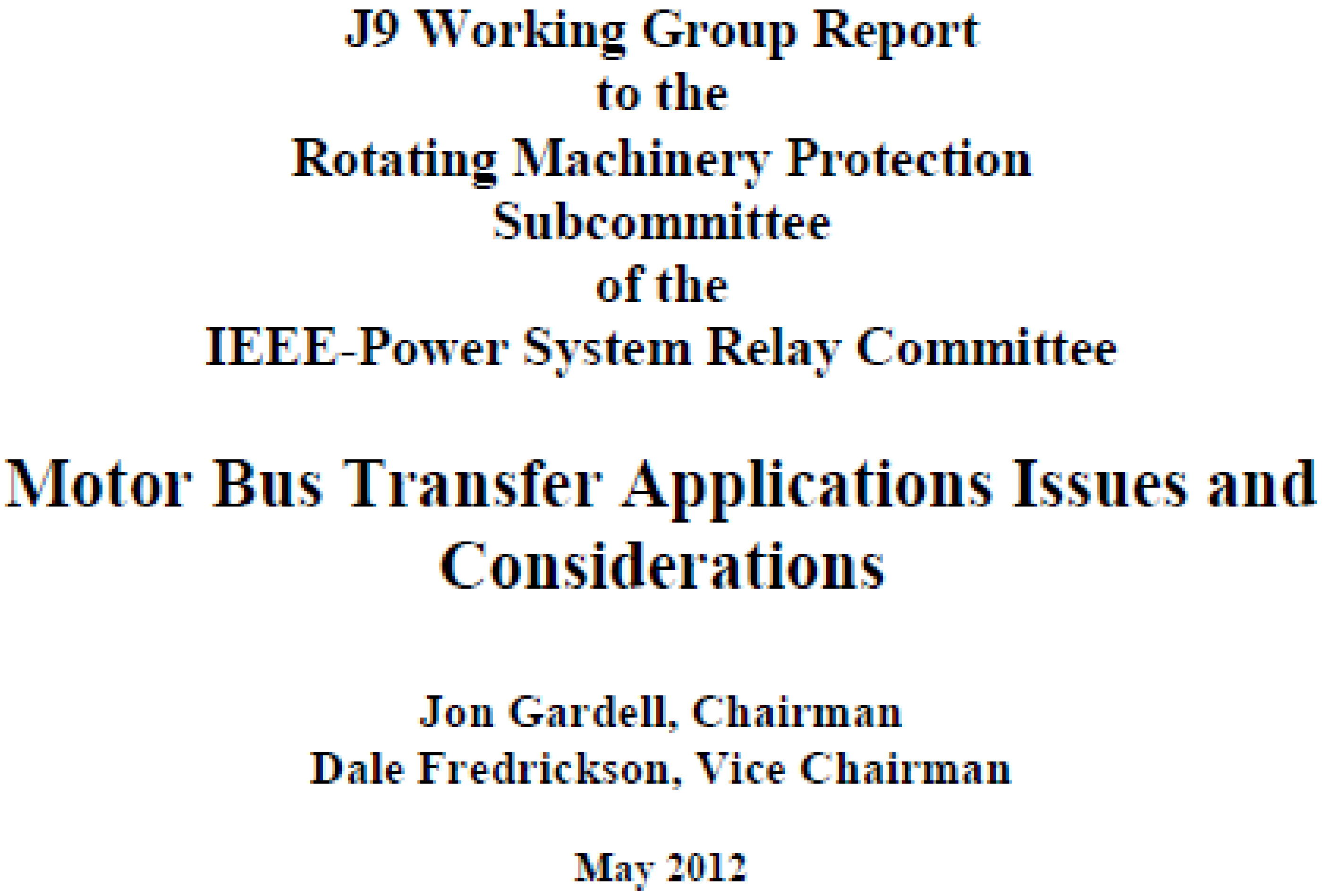
Power Plant Track
Thursday, August 7, 2025
Day 4 – Session 1

Reference documents:

1. Motor Bus Transfer Applications, Issues and Considerations, IEEE Power System Relay Committee, Rotating Machinery Protection Subcommittee, J9 Working Group Report, May 2012.
2. IEEE Std C37.96-2012 Guide for AC Motor Protection Polyphase Induction Motors for Power Generating Stations, American National Standard ANSI C50.41-2012.
3. Murty V.V.S. Yalla , Arman Vakili and Thomas R. Beckwith, “Calculation of Transient Torques on Motors During a Residual Voltage Motor Bus Transfer” IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 56, NO. 6, NOVEMBER/ DECEMBER 2020, pp. 6104-6116.

Webpage link for IEEE PES PSRC reports:

http://www.pes-psrc.org/kb/published/reports.html



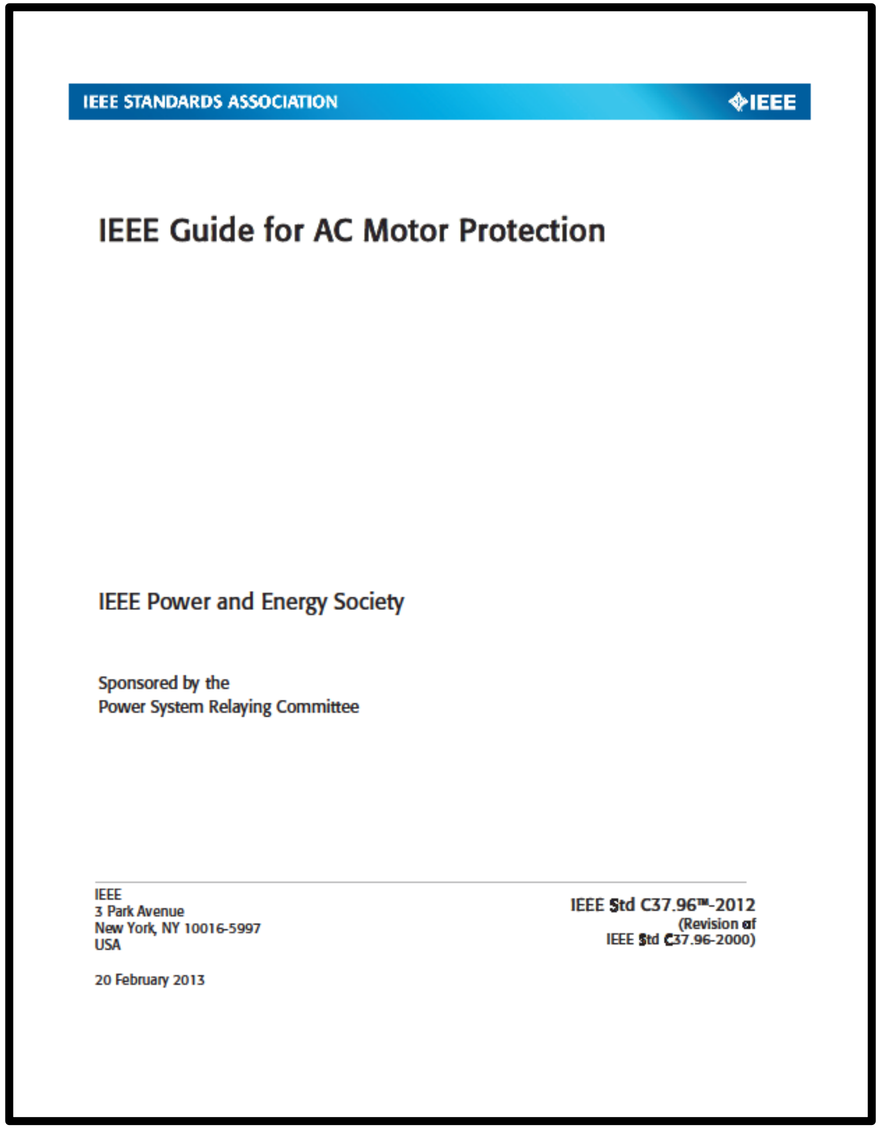
J9 Working Group Report
to the
Rotating Machinery Protection
Subcommittee
of the
IEEE-Power System Relay Committee

Motor Bus Transfer Applications Issues and Considerations

Jon Gardell, Chairman
Dale Fredrickson, Vice Chairman

May 2012

IEEE Std C37.96-2012 IEEE Guide for AC Motor Protection



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IEEE Std C37.96™-2012
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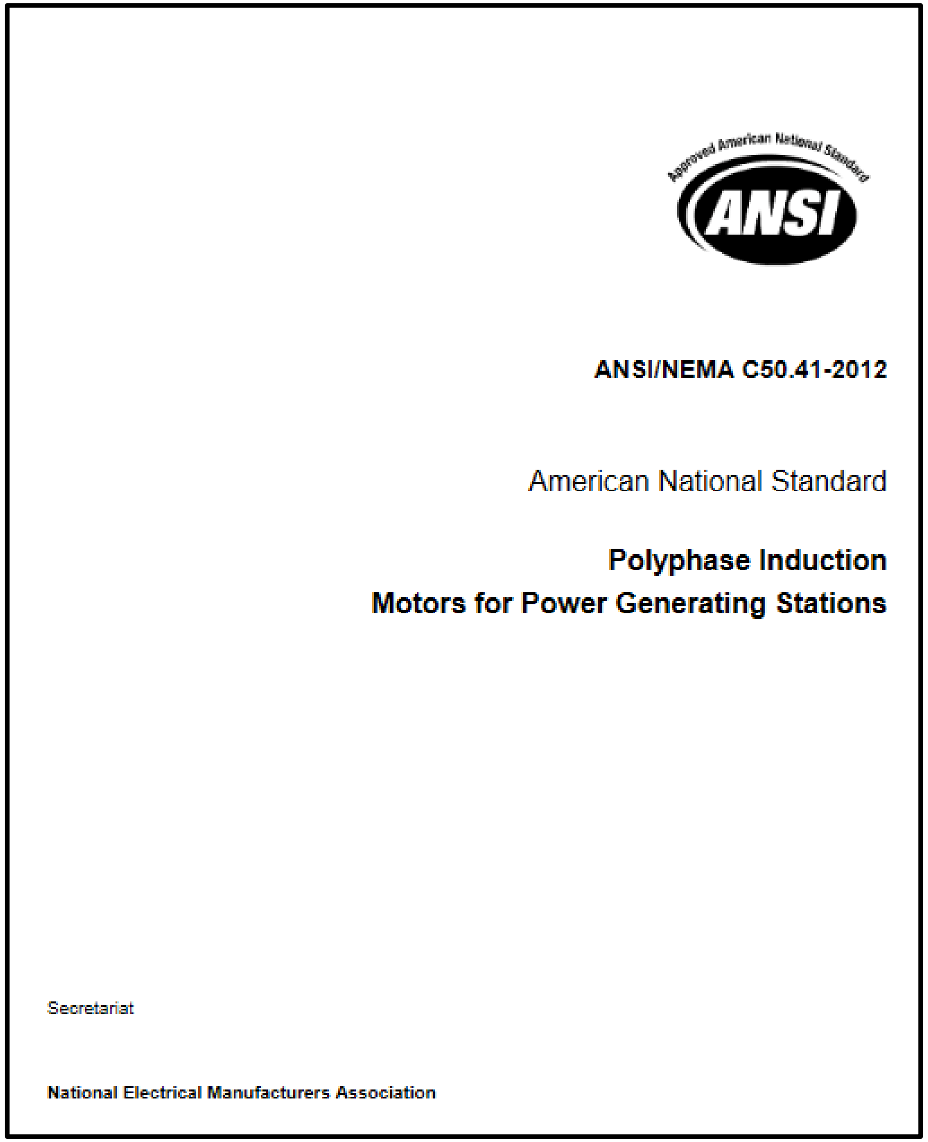
ANSI/NEMA C50.41-2012



ANSI/NEMA C50.41-2012

American National Standard

Polyphase Induction
Motors for Power Generating Stations

Secretariat

National Electrical Manufacturers Association

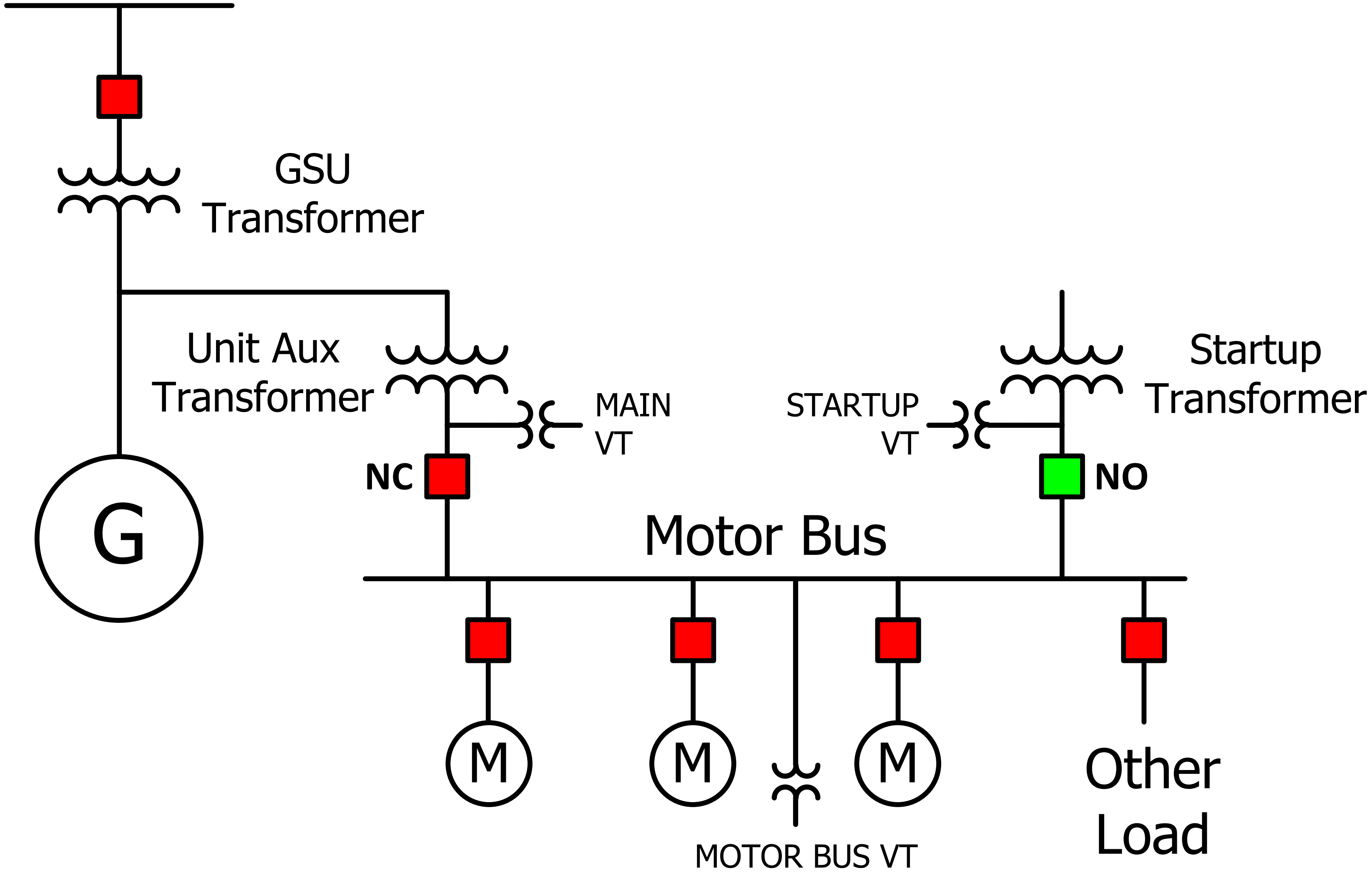
Introduction

- To maintain plant operation and process continuity, motor buses may require transfer from a present (old) source to a new source:
  - Power plants.
  - Industrial facilities.
- 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.
- Larger motors, of both the synchronous and induction variety, may require comprehensive, integrated source transfer strategies in order to avoid mechanical damage.
- The coast down period and resultant voltage and frequency decay may take seconds, and unsupervised source transfer may cause damage
- During improper transfer, mechanical damage may occur in the motor, the coupling to the load or the load itself, and is primarily caused by excessive shaft torque.
- The total mission of a MBT system is:
  - Maintain process continuity.
  - Effect source transfers so as not to cause any damage to the motors and connected loads.

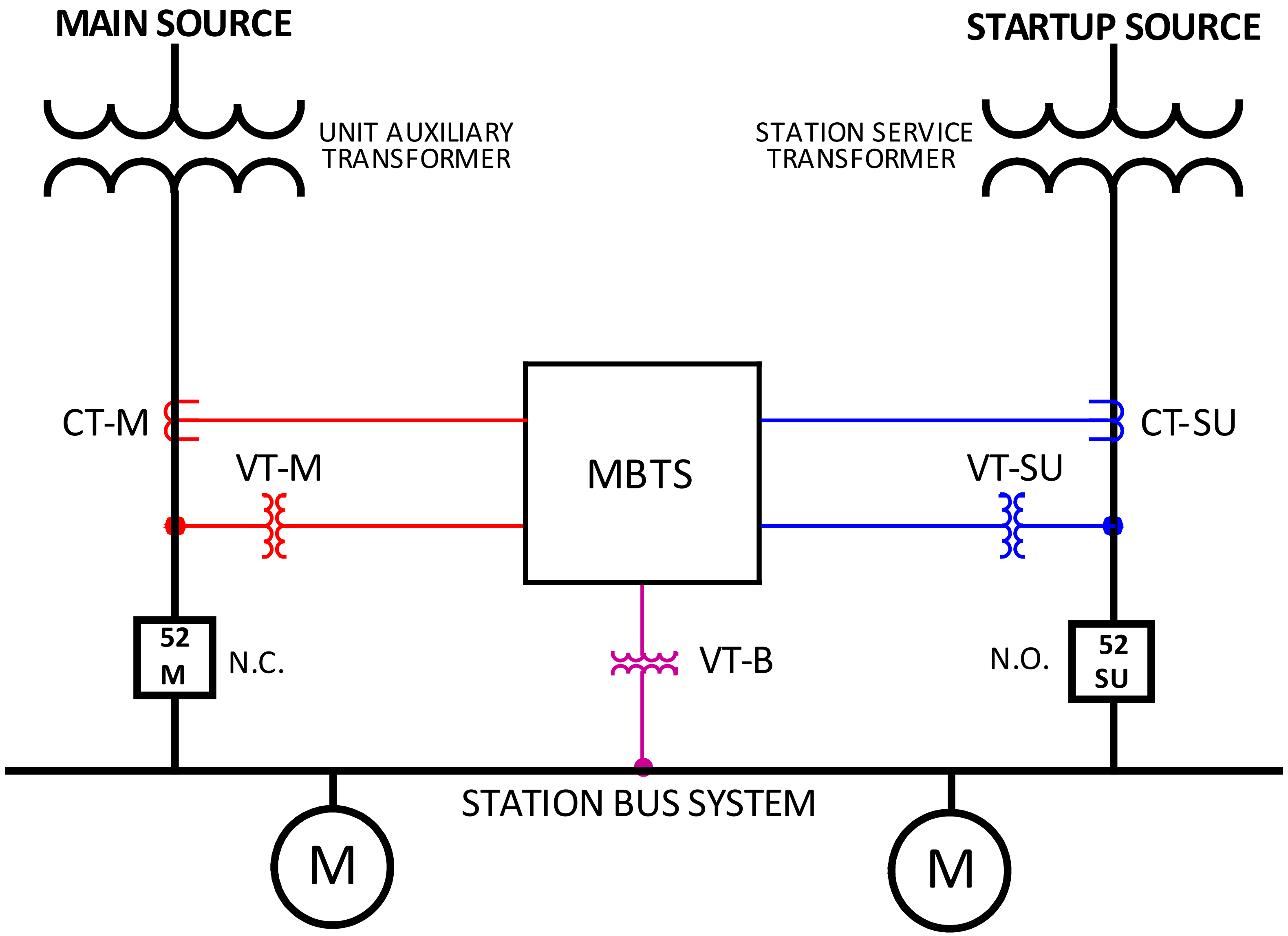
Why Transfer Motor Load Sources?

Planned	▪ Plant Start Up and Shut Down ▪ Maintenance ▪ For power supply security, transfer to onsite source when storm approaches
Unplanned	▪ Fault on present supply ▪ Interruption on present supply

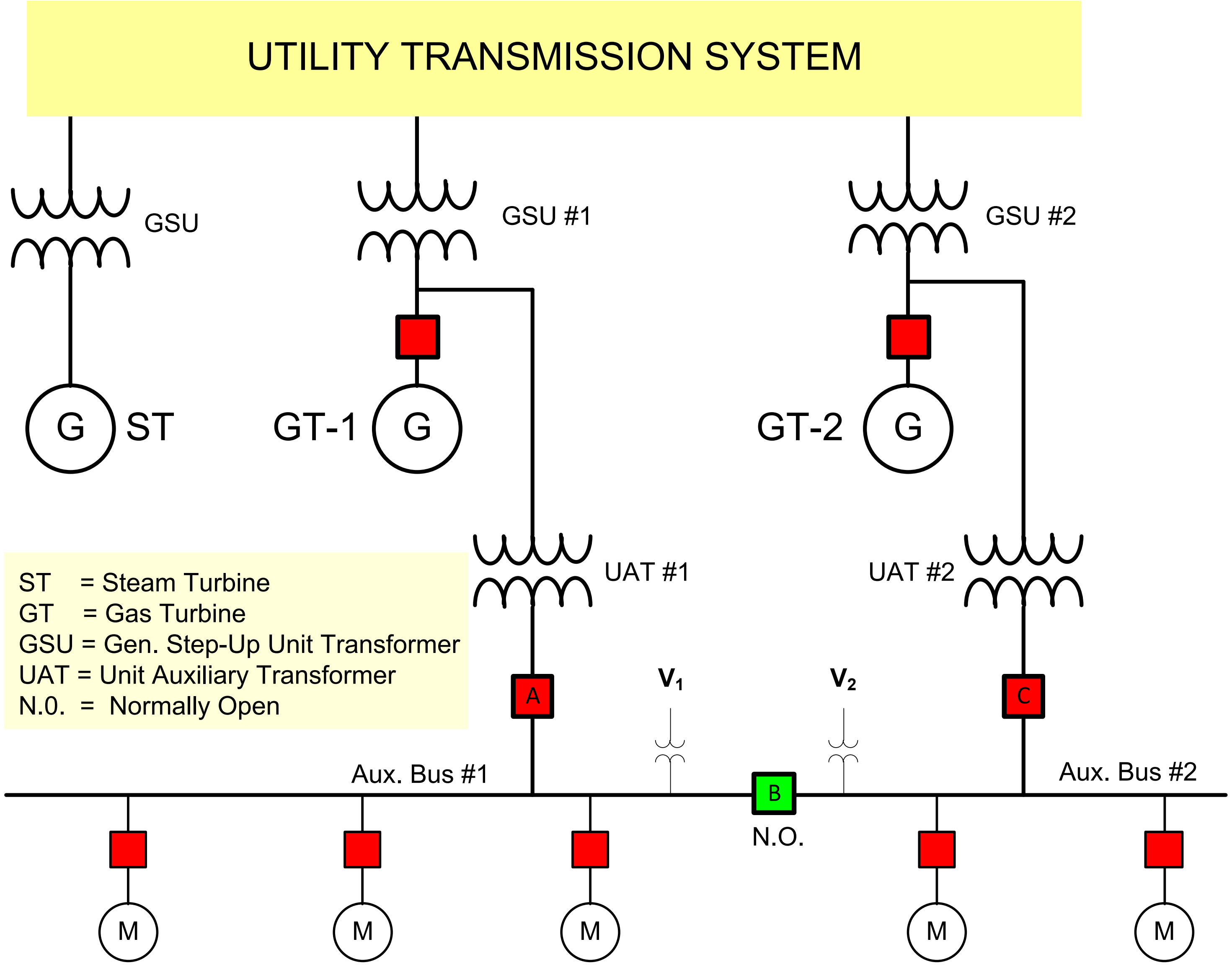
Unit-Connected Generator Motor Bus



Two-Breaker Configuration (Primary-Backup)

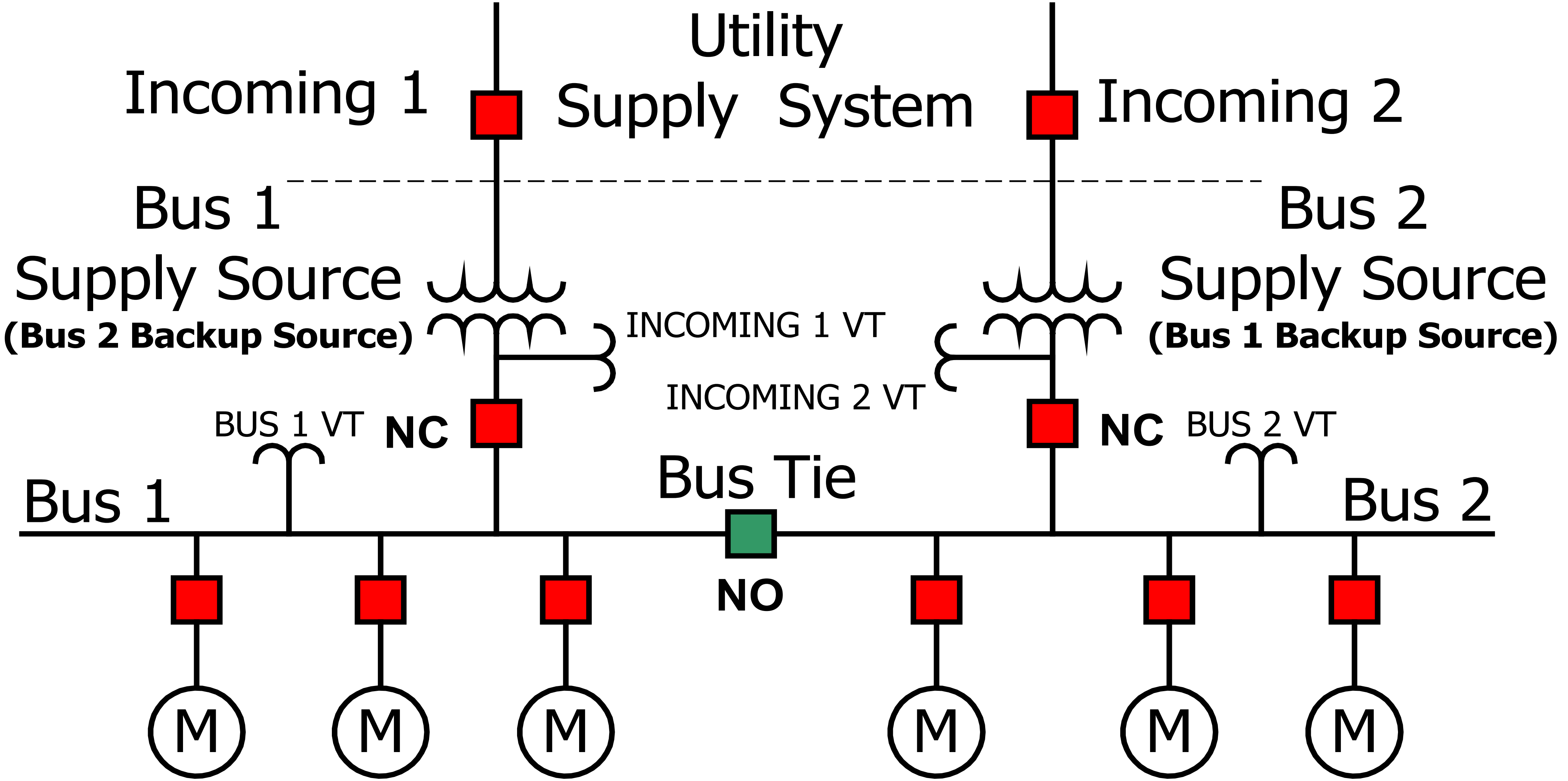


Combined Cycle Plant Motor Bus



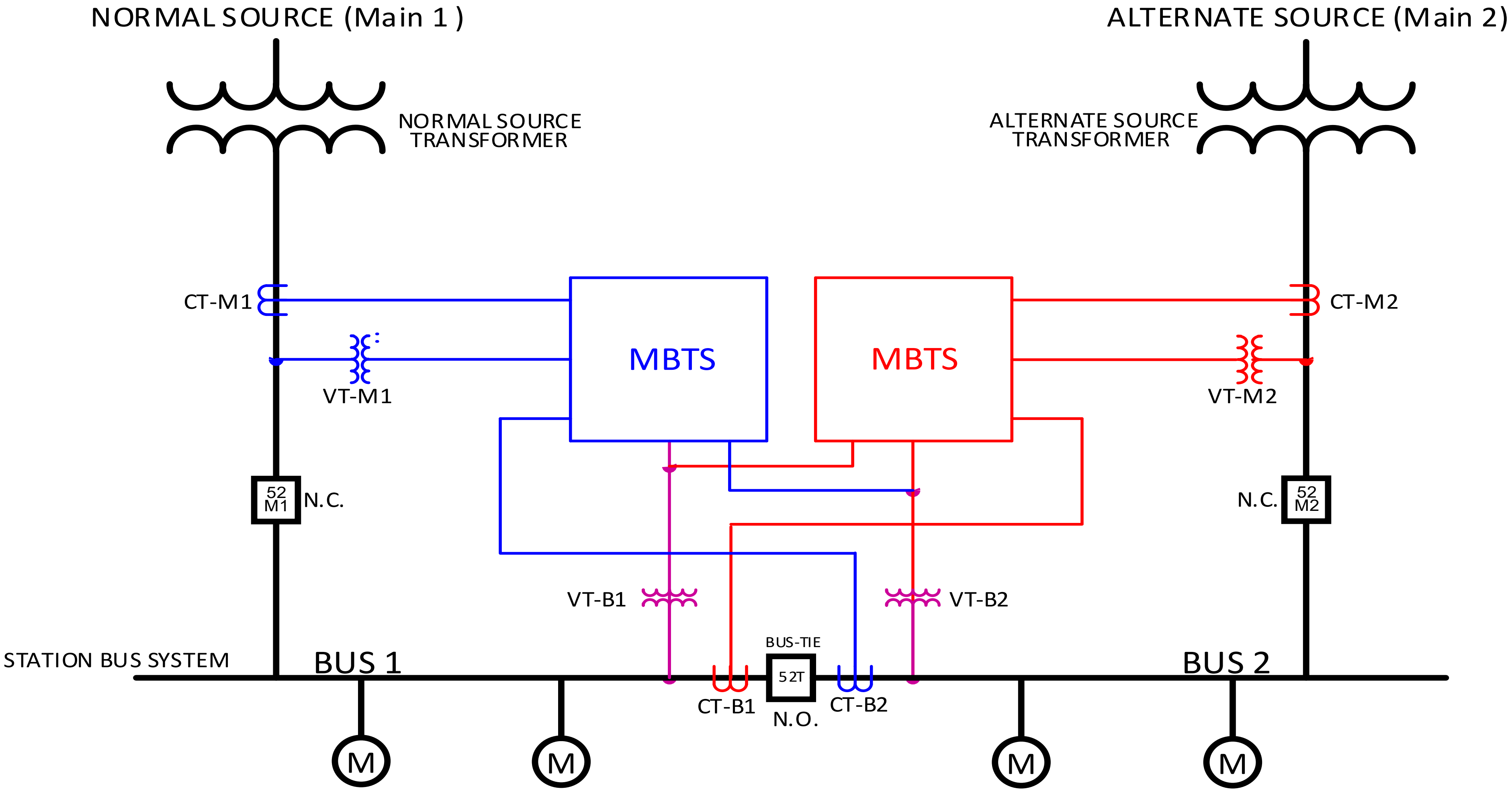
ST = Steam Turbine
GT = Gas Turbine
GSU = Gen. Step-Up Unit Transformer
UAT = Unit Auxiliary Transformer
N.0. = Normally Open

Typical Industrial Plant One-Line



Three-Breaker Configuration (Main-Tie-Main)

Do not want to put “all eggs in one basket,” with both sides of a main-tie-main configuration in one box.



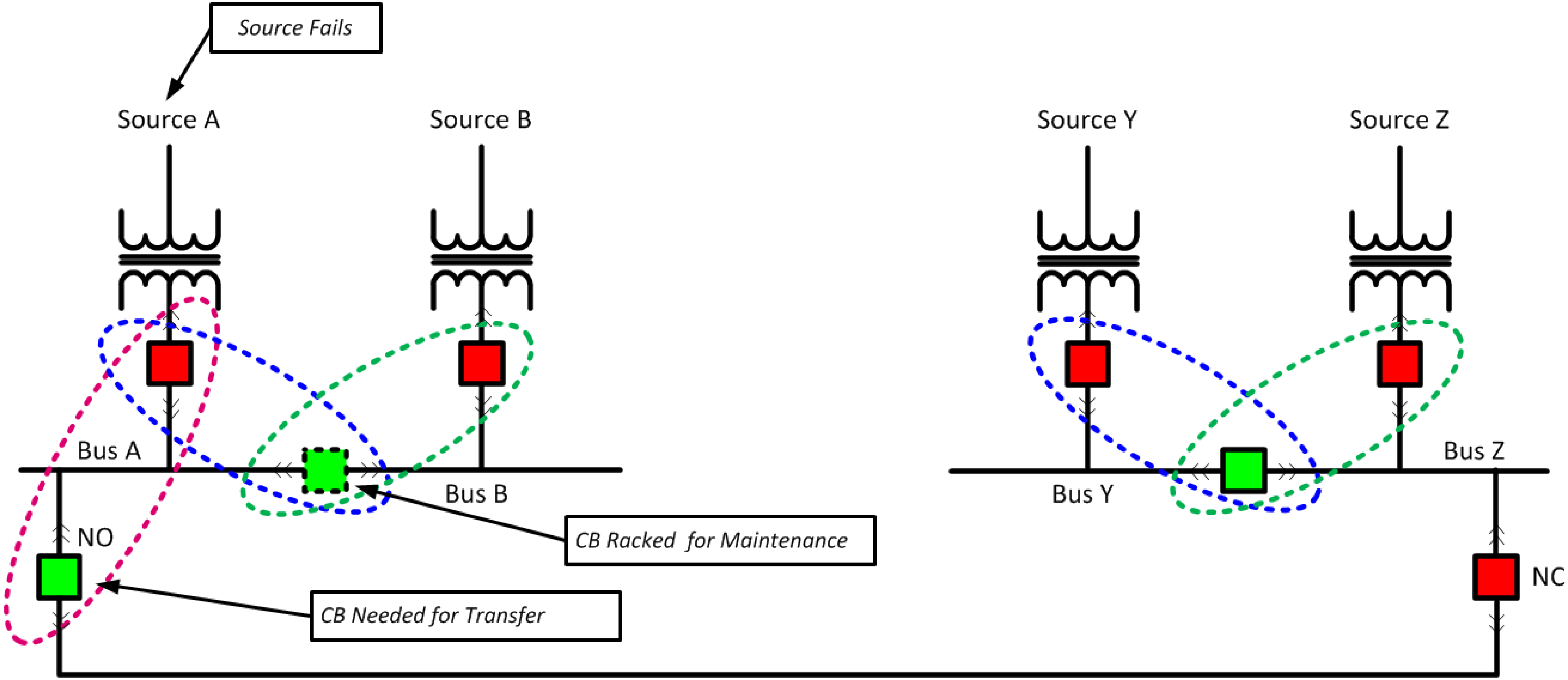
The Core "Bus with Two Sources" Primary-backup Topology in one MBT System – Why?

- For applications requiring only a primary-backup topology, do not want to complicate the system with an unnecessary configuration.
- In the core primary-backup topology, a motor bus transfer system must provide full 3-phase inputs for both sources and the motor bus. For the requisite reliability of a critical process transfer, it is mandatory to measure all three phases of all inputs.
- With 40 years of experience in motor bus transfer, we have identified many other topologies other than the primary-backup and main-tie-main. One could not possibly imagine getting these all-in-one box. To name a couple, there are the double-option primary-backup and the double-option main-tie-main.

Motor Bus Transfer

Double-Option Main-Tie-Main

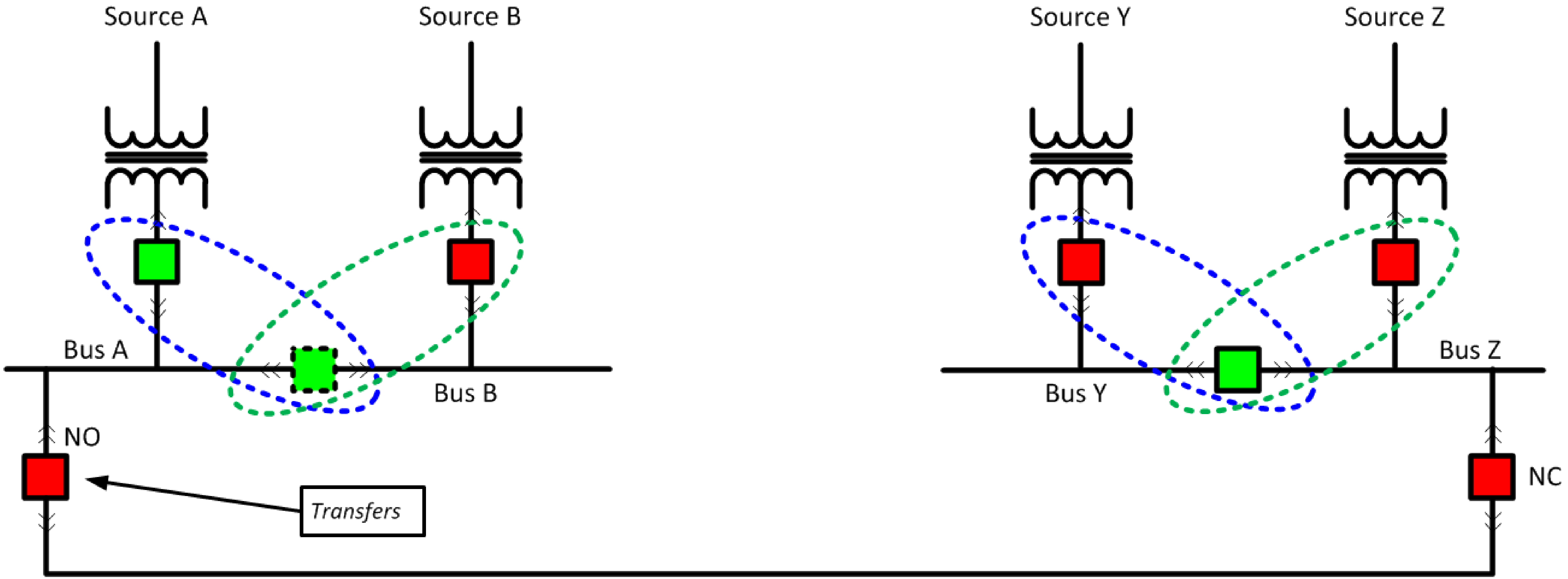
- Multiple Source Selection
- CB Racked for Maintenance



Motor Bus Transfer

Double-Option Main-Tie-Main

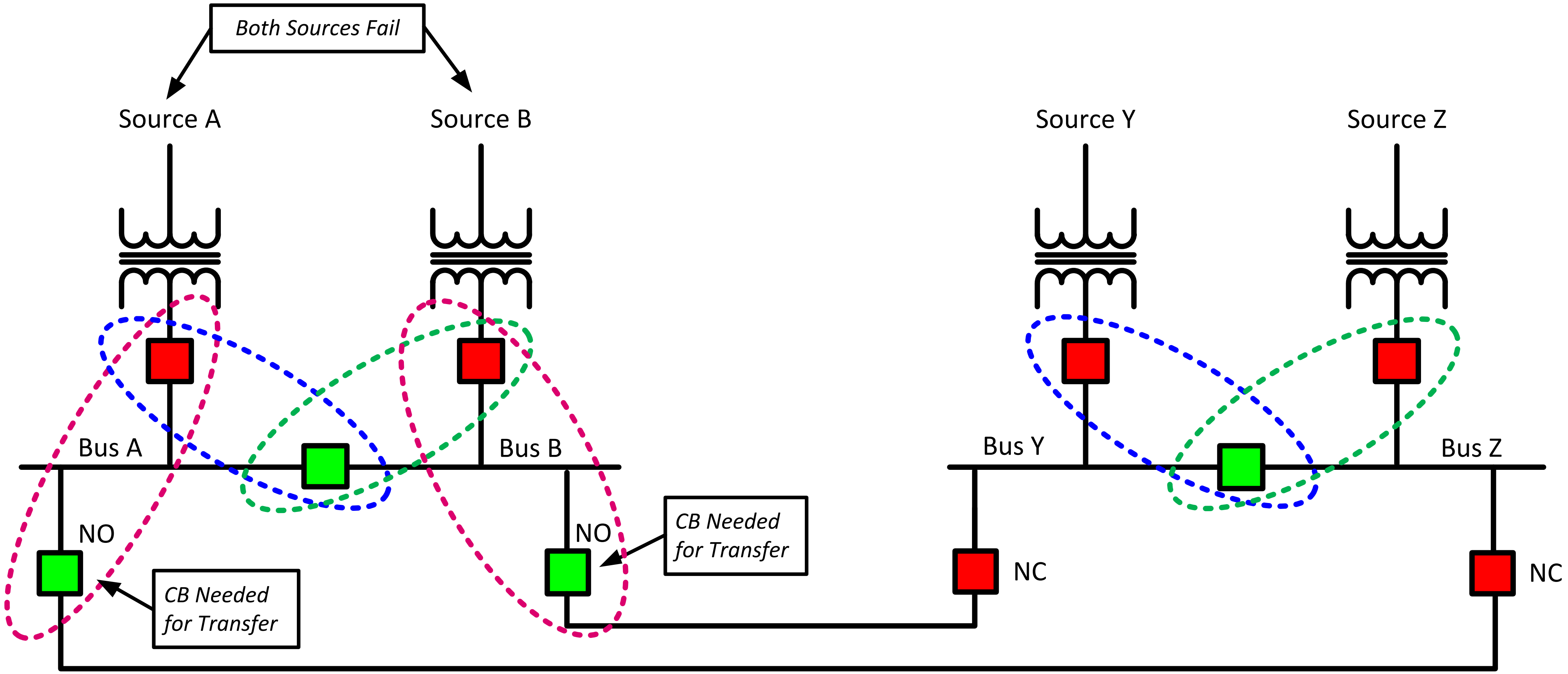
- Multiple Source Selection
- CB Racked for Maintenance



Motor Bus Transfer

Double-Option Main-Tie-Main

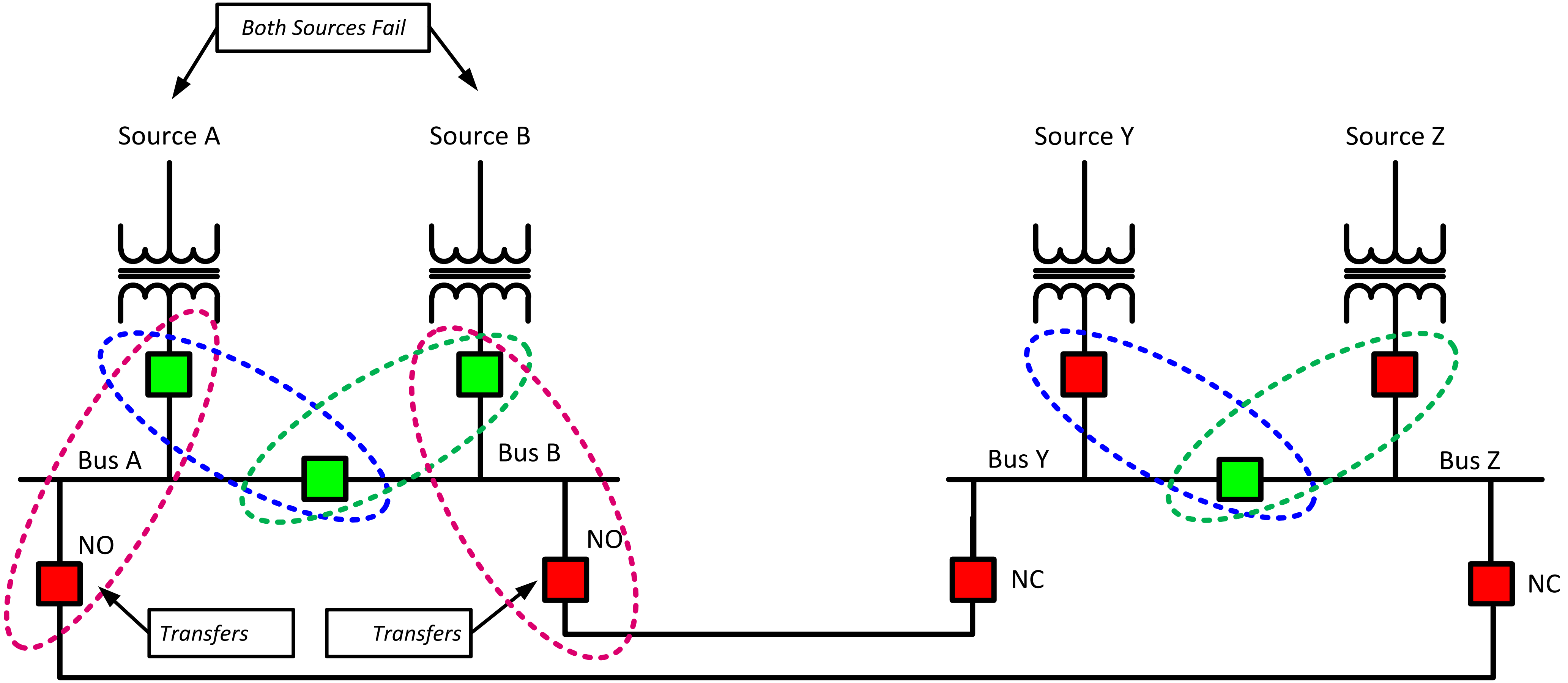
- Multiple Source Selection
- Both Sources Fail



Motor Bus Transfer

Double-Option Main-Tie-Main

- Multiple Source Selection
- Both Sources Fail



Both Sources Fail

Transfers

Transfers

Motor Bus Transfer Classification

- Automatic Initiate – Unplanned
- Manual Initiate – Planned. But Keep Automatic Transfer Enabled!

Why? If an unforeseen event occurs while Manual Initiate is selected that requires an unplanned transfer, the operator will not be able to react quickly enough to initiate the transfer!

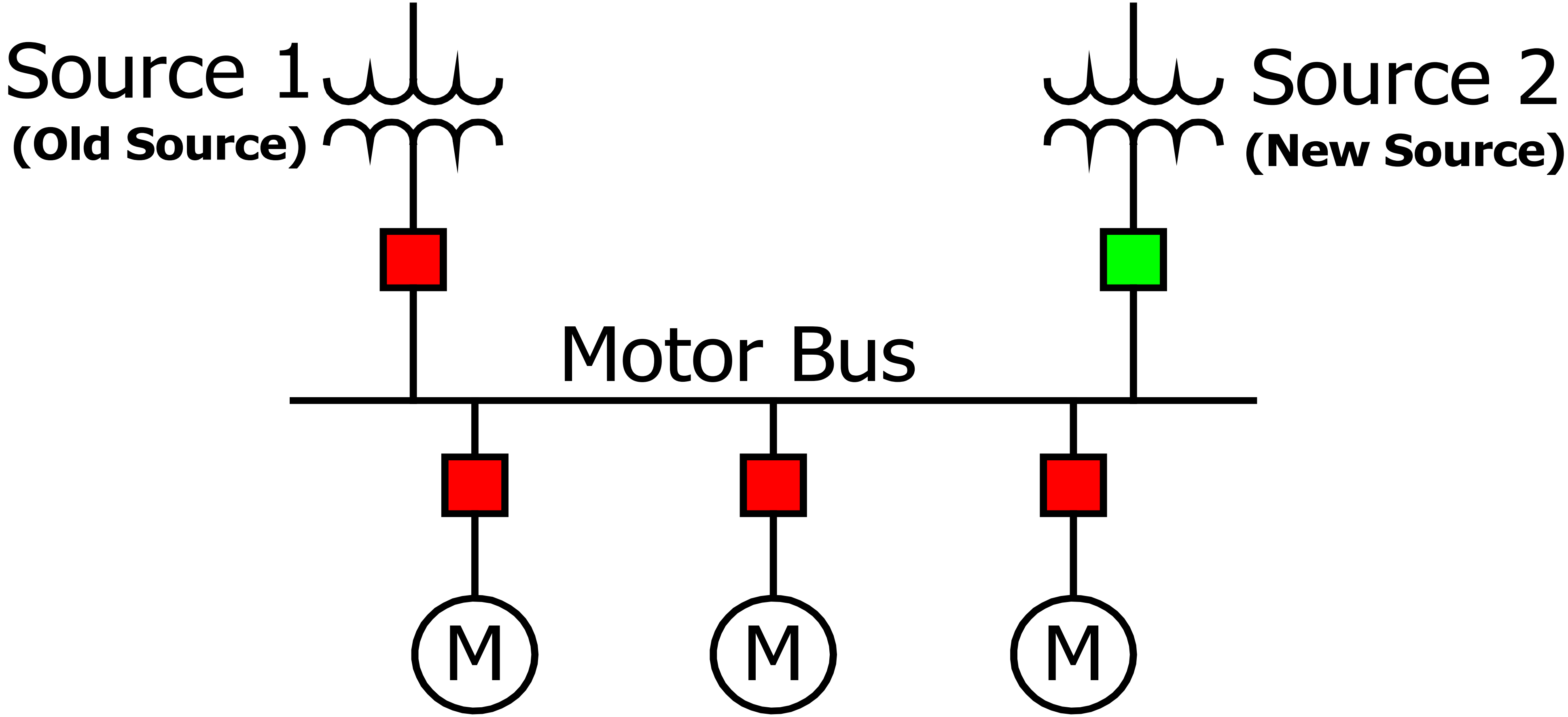
Motor Bus Transfer Classification

- Closed Transition
  - Hot Parallel Transfer
- Open Transition - Methods
  - Fast Transfer
  - In-Phase Transfer
  - Residual Voltage Transfer
  - Fixed Time Transfer
- Open Transition - Modes
  - Sequential
  - Simultaneous

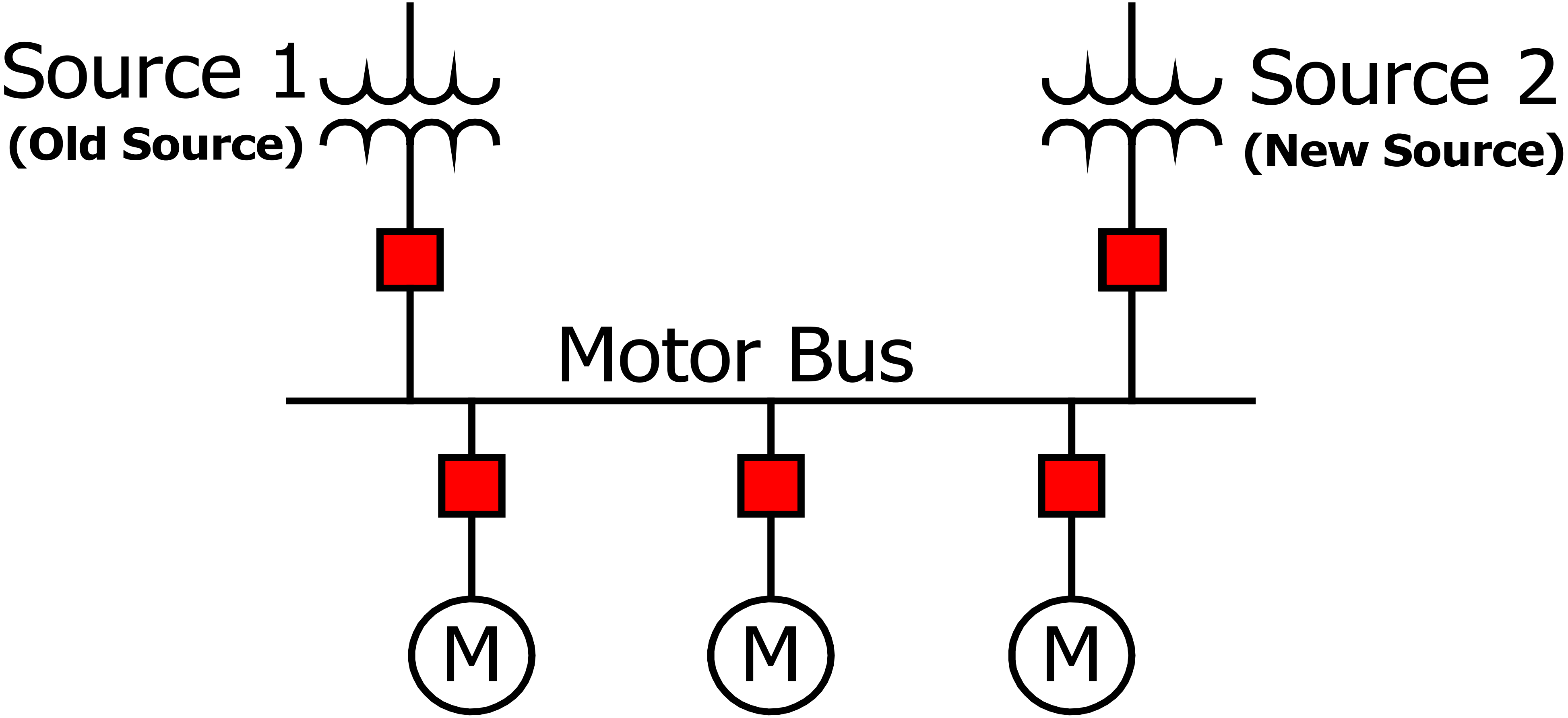
Closed Transition – Hot Parallel Transfer

- New source connected to the motor bus before the old source is tripped. Transfers sources without interruption.
- Voltages and phase angle between the motor bus and the new source must be evaluated prior to the transfer to assure that:
  - Motor bus and the new source are in synchronism.
  - New source voltage is within acceptable limits.
- If a transfer is initiated and the new source breaker is closed, while the old source breaker remains closed, the transfer system must immediately trip the old source breaker. This allows parallel transfer but prohibits inadvertent parallel operation.
- Also, if no transfer was initiated, trip provisions can be programmed to trip a new source breaker that was inadvertently closed.

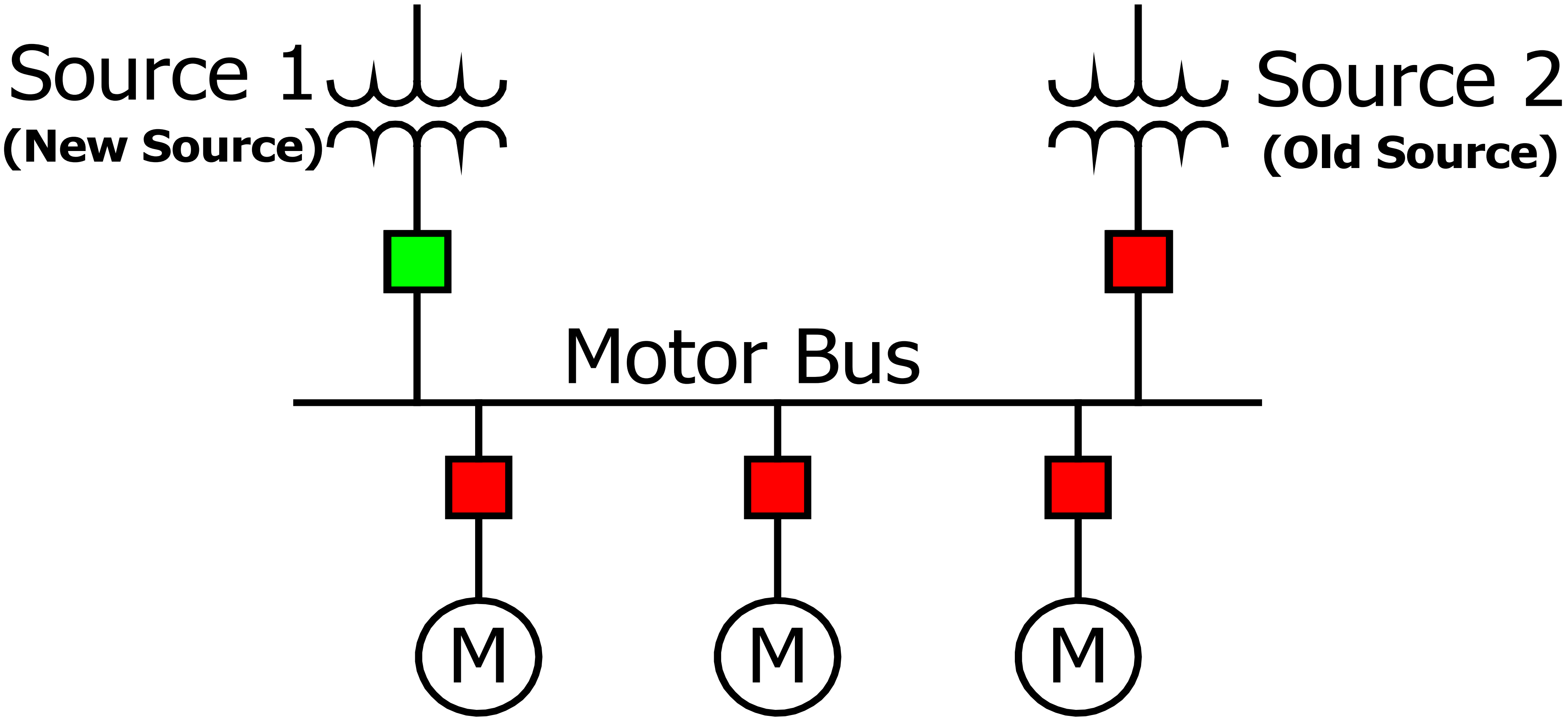
Closed Transition – Hot Parallel Transfer



Closed Transition – Hot Parallel Transfer



Closed Transition – Hot Parallel Transfer



Closed Transition - Hot Parallel Transfer

Advantages

- No disruption of plant process.
- Simple to implement with sync-check relay supervision across new source breaker.
- No transient torque on motors during the transfer.

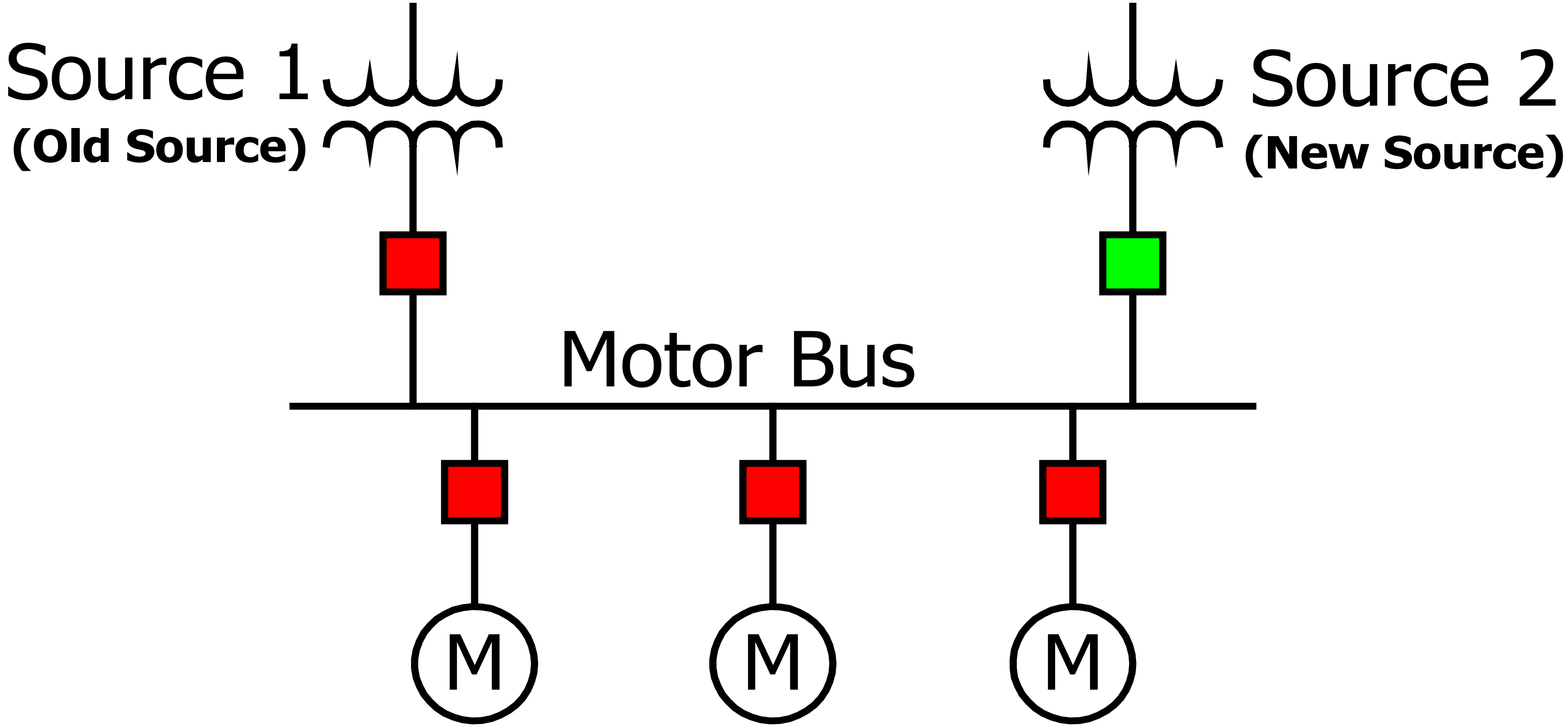
Disadvantages

- Will not work during transient (emergency) conditions. **Do not want to connect “good” source to a source that is having problems.**
- Exposure to double-fed faults during parallel operation.
- The two sources may not be derived from the same primary source and might have a large standing phase angle between them, preventing a hot parallel transfer.
- Design must ensure that a parallel condition is temporary, and breaker failure is a concern.

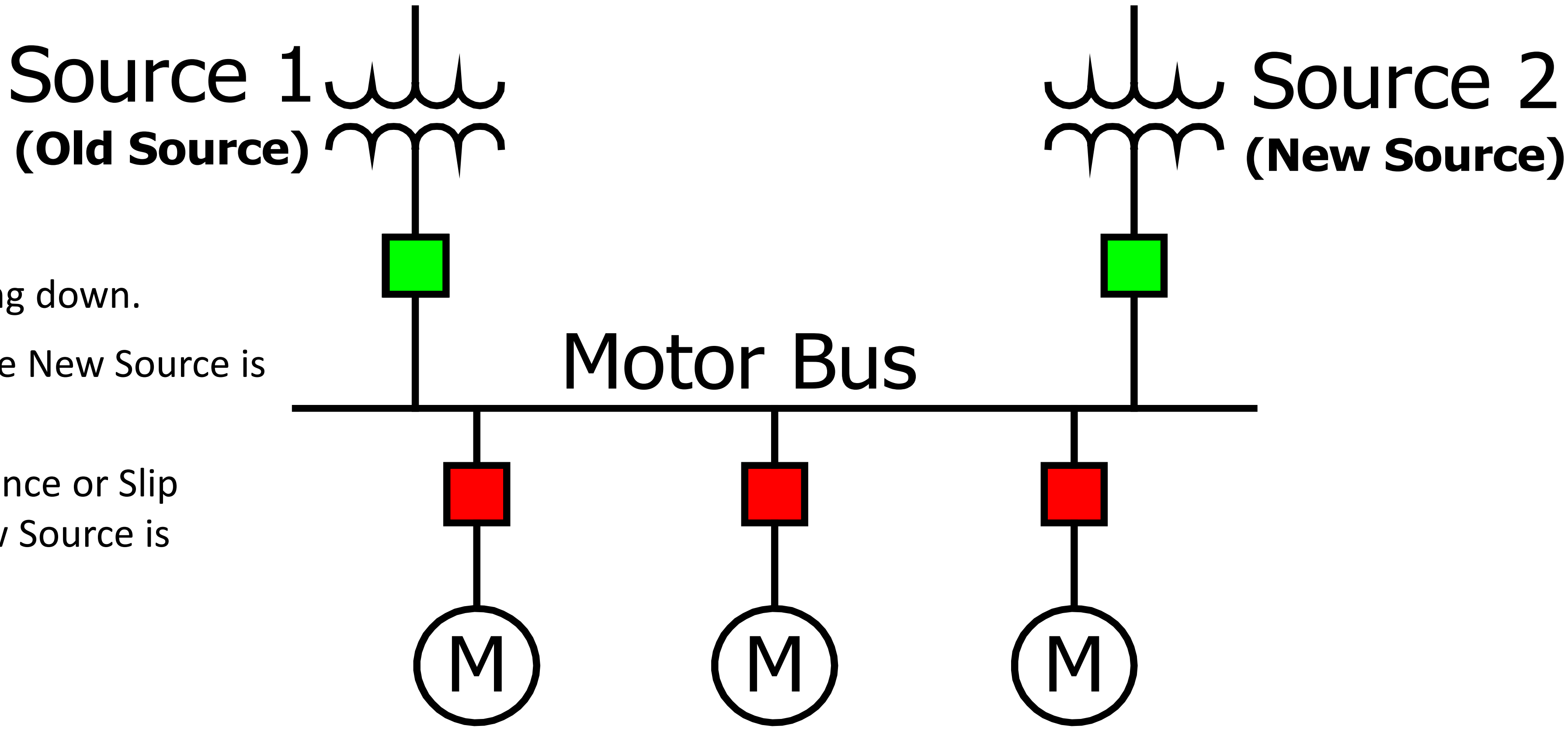
Open Transition Motor Bus Transfer

- Old Source Breaker is tripped before the New Source Breaker is closed.
- Phase Angle and Slip Frequency between the Motor Bus and the New Source must rapidly be evaluated prior to and during the transfer.

Open Transition



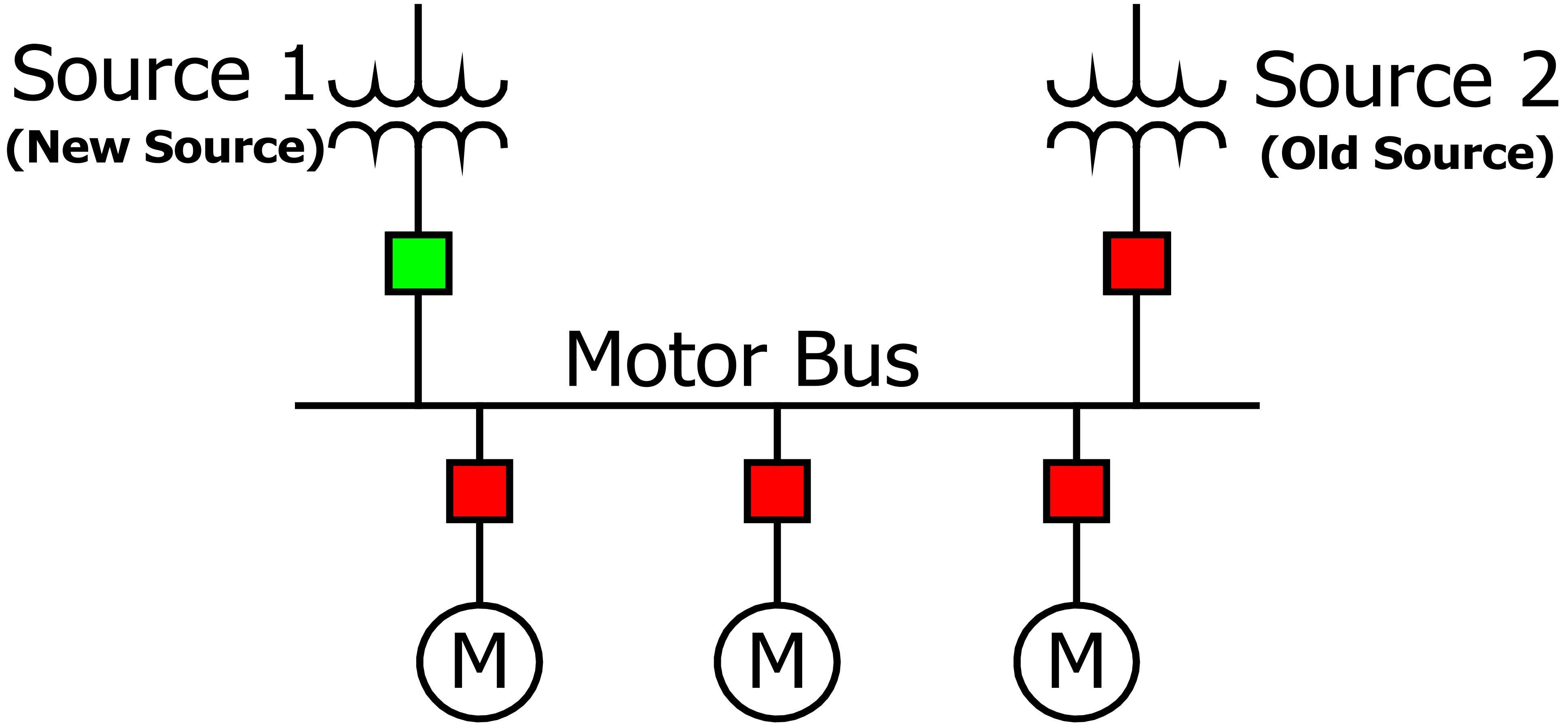
Open Transition



- Motors are slowing down.
- Phase Angle to the New Source is accelerating.
- Frequency Difference or Slip Frequency to New Source is increasing.

Open Transfer Time = The time from the Old Source Breaker trip to the New Source Breaker close.

Open Transition



Open Transition

Methods

- Fast Transfer
- In-Phase Transfer
- Residual Voltage Transfer

Modes

- Sequential Mode
- Simultaneous Mode

Open Transition Motor Bus Transfer

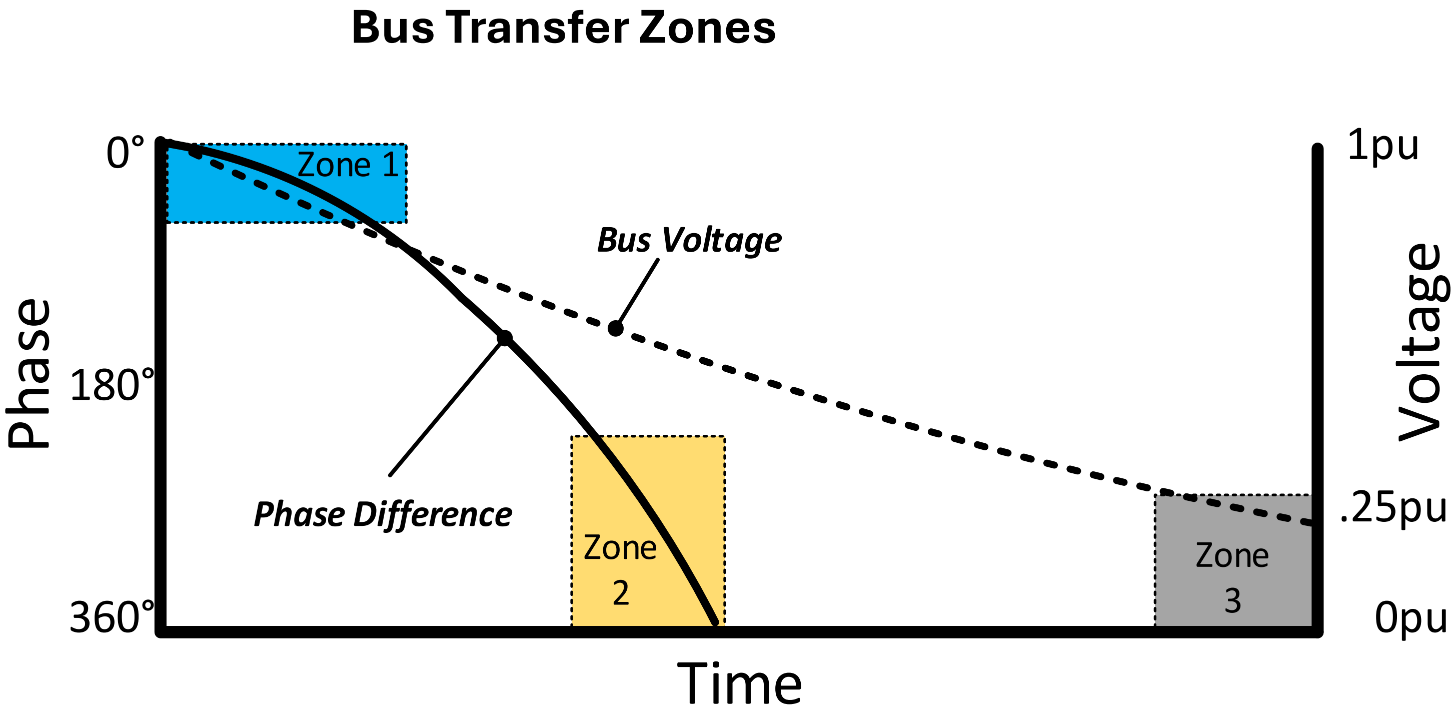
- Fast Synchronous Methods ensure that the Motor Bus and the New Source are in synchronism at the point of closure of the New Source Breaker:
  - Fast Transfer.
  - In-Phase Transfer.
- Slow Method that waits for the Motor Bus Voltage to decay below .30 per unit and ignores synchronism:
  - Residual Voltage Transfer.
  - Like a roulette wheel; round and round she goes and where she stops nobody knows.
- Modes:
  - 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.

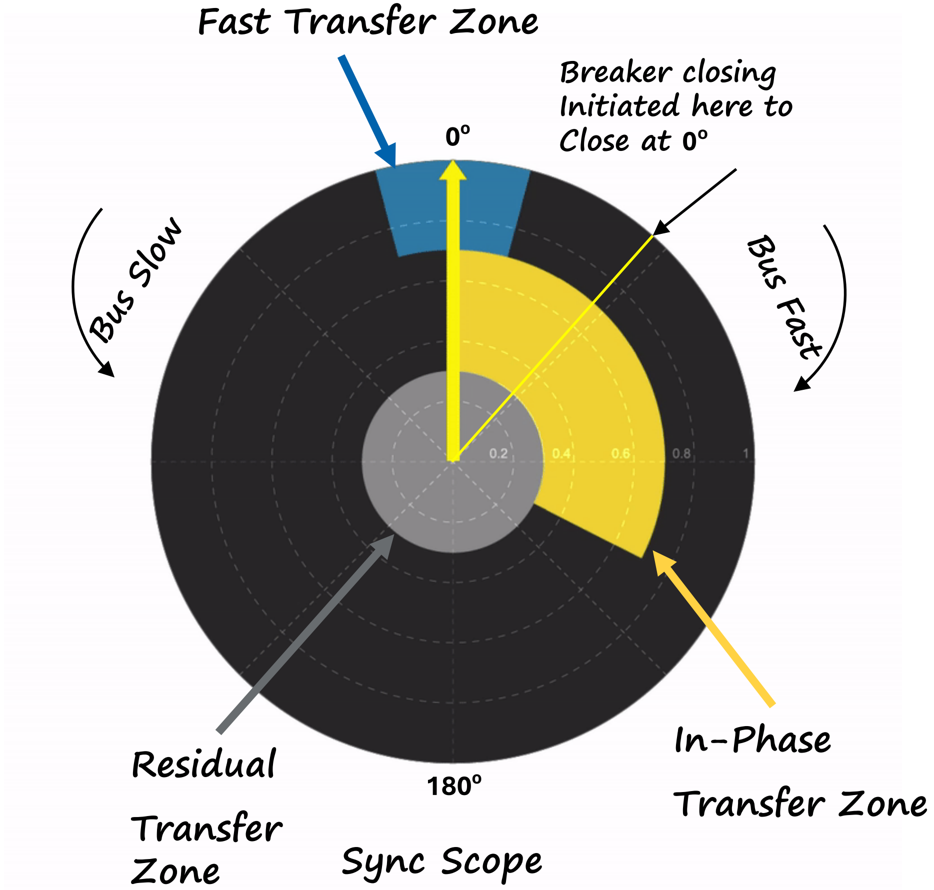
Open Transition Methods:

Fast Transfer (Zone 1)

In-Phase Transfer (Zone 2)

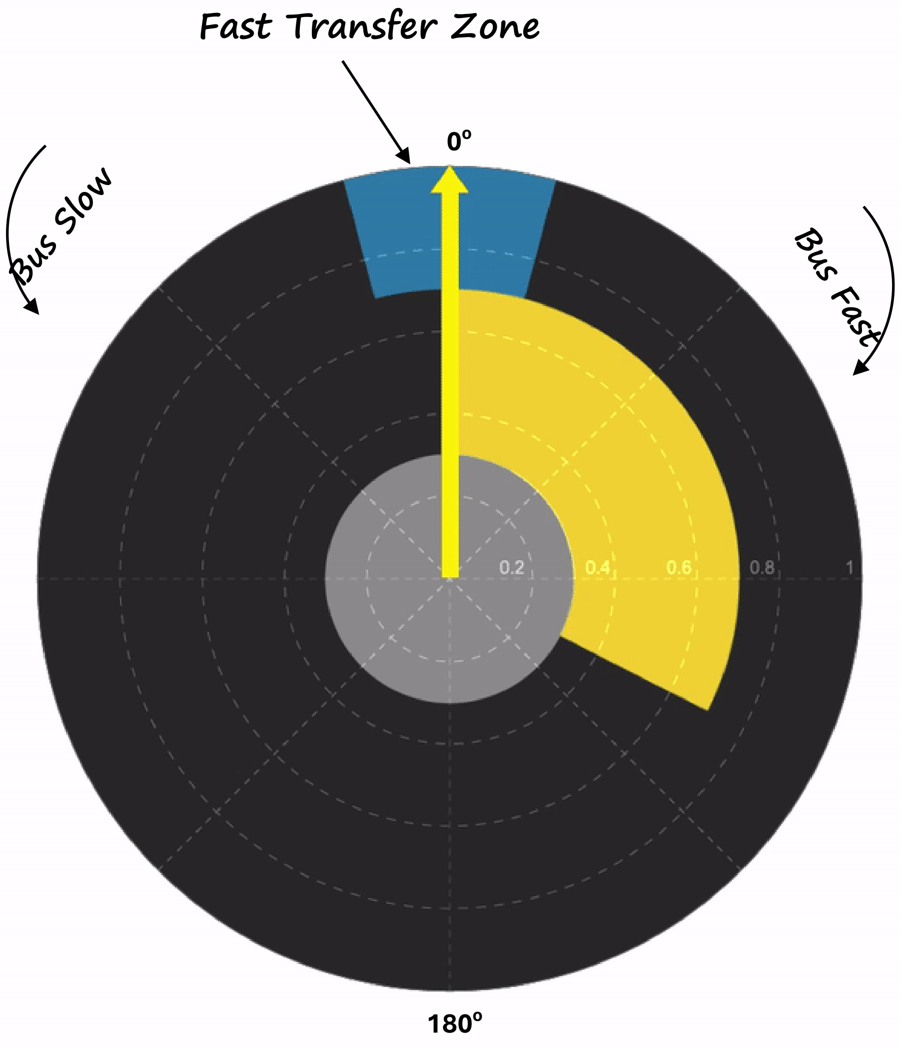
Residual Voltage Transfer (Zone 3)





Fast Transfer Method

- New Source Breaker is closed if the phase angle between the Motor Bus and the New Source is within or moves into the Phase Angle Limit
- This method requires high-speed sync-check supervision
  - Must be able to block high speed - 3ms response
  - Must be able to close high speed - 3ms response
- Circuit breaker closing is also supervised by an Upper and Lower Voltage Limit check on the new source



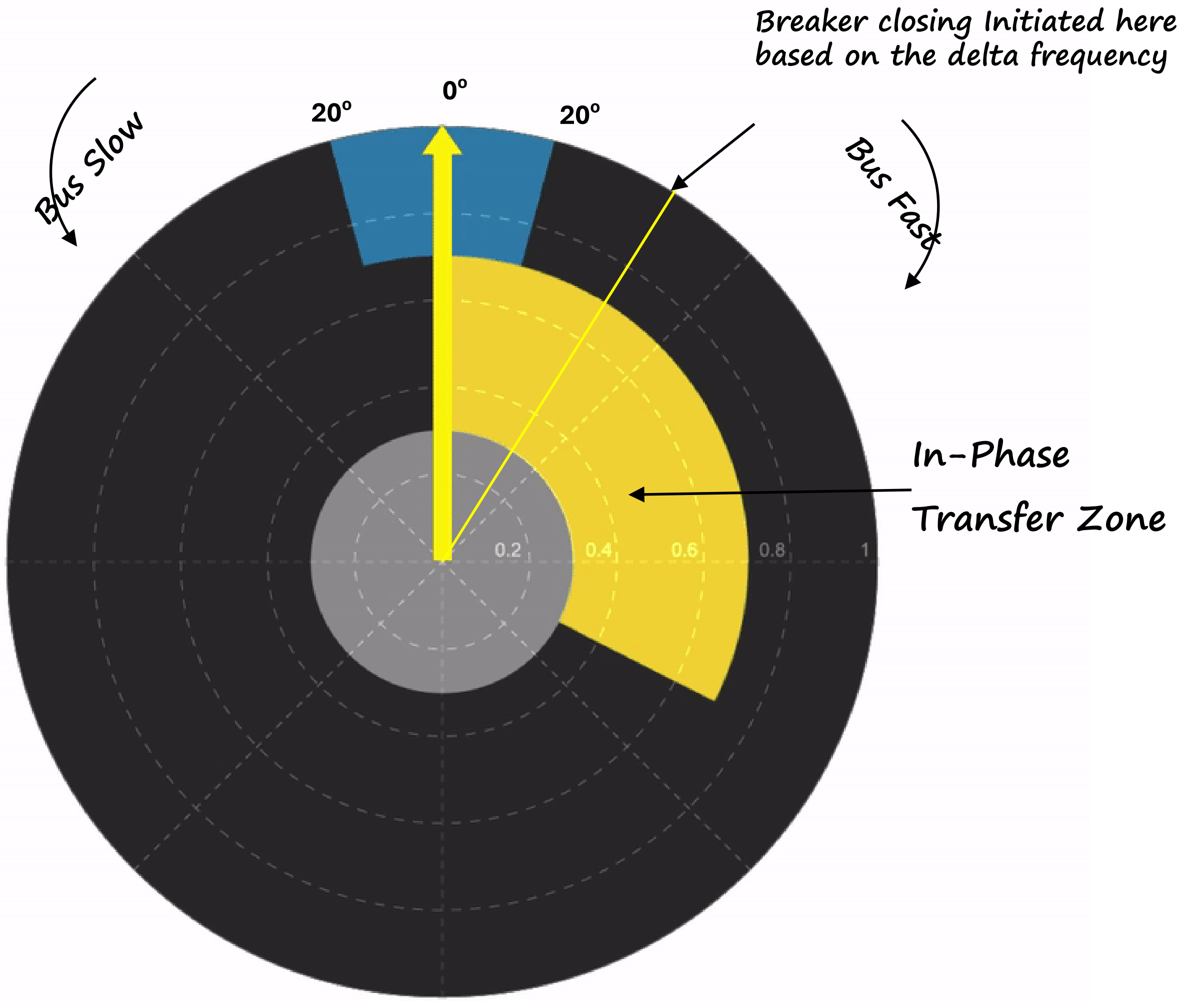
Sync Scope

Fast Transfer Method

- Presently, the majority of fast transfer systems are NOT supervised by high-speed sync-check relays!
- In many cases, Fast Transfer cannot be correctly performed without a high-speed sync check relay.
- Some modern solid-state or microprocessor-based sync check elements have a minimum time delay of 0.1 second or 100 milliseconds.
  - By the time they respond to the phase angle of a decaying motor bus, the possibility of a successful transfer is long gone.
  - Worse yet, the contacts may be still closed and permit transfers at excessive angles and damage critical motors.

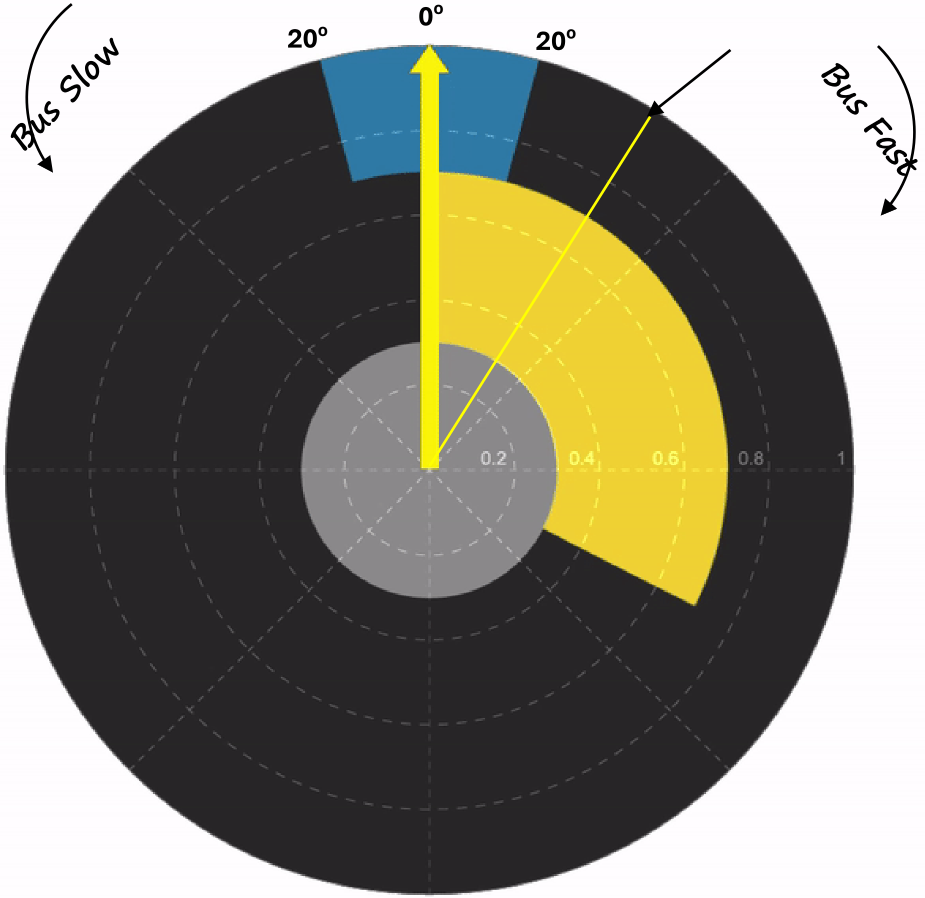
In-Phase Transfer Method

- Takes into account the decaying motor bus frequency, and the increasing slip frequency between the Motor Bus and the New Source.
- Sends a New Source Breaker close command at an Advance Angle to compensate for the breaker close time so the motors are connected to the new source near zero degrees.



In-Phase Transfer Method

- The speed of the voltage and frequency decay can be much faster and depends on the inertia of the connected loads.



Breaker closing Initiated here based on the delta frequency

In-Phase Transfer Method

- The new source breaker will be closed by predicting movement through phase coincidence between the motor bus and the new source during the In-Phase Transfer Enable Window.
- Due to the decaying motor bus frequency, slip frequency and rate-of-change of frequency between the motor bus and the new source must be calculated to correctly compensate for the breaker closing time.
  - High speed (quarter-cycle or less) response is recommended.
- Predicted phase coincidence is used with breaker closing time of the new source breaker to achieve a breaker close at phase coincidence.
- Additional supervision:
  - Upper and Lower Voltage Limit check on the new source.
  - Slip (ΔF) Frequency Limit between the motor bus and the new source.

Fast and In-Phase Transfer Methods

(aka: Synchronous Transfers)

Advantages

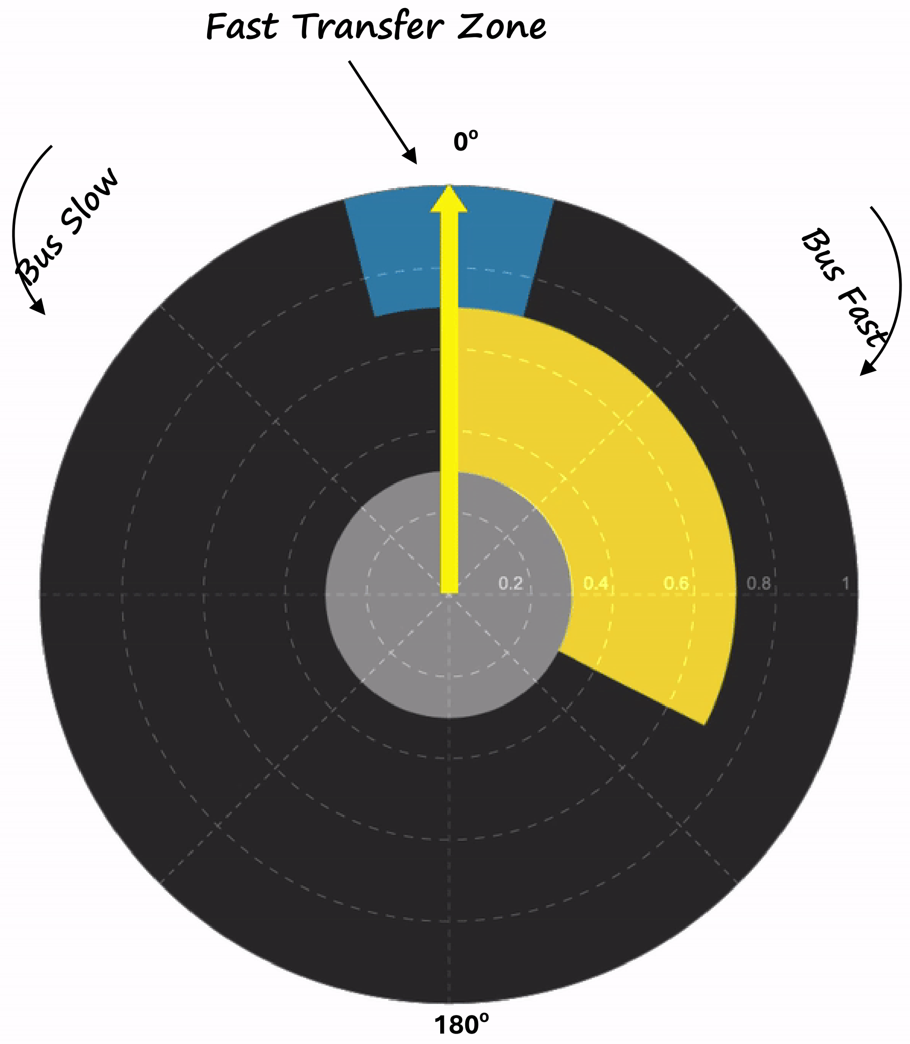
- No disruption of plant process.
- Minimizes transient torque on motors during the transfer.
- Can be used during fault conditions.
- Can be used for planned transfers.
- Applicable when two sources are not in sync or within an acceptable small static phase angle difference of each other.
- No concerns of exceeding fault ratings of circuit breakers or through fault rating of transformers due to paralleling sources.
- Applicable for use where two sources may not be derived from the same primary source, or on a single source.

Disadvantages

- None when performed correctly.

Residual Voltage Transfer Method

- The new source breaker will be closed if the motor bus voltage drops below the Residual Voltage Transfer Limit.
- IGNORES SYNCHRONISM.
- Since phase angle and slip frequency is unsupervised, this method must prevent closure of the new source breaker until the motor bus voltage drops below a predetermined voltage limit (usually < 0.30 pu).
  - This ensures compliance with the 1.33 pu V/Hz limit per ANSI Standard C50.41.
- Voltage measurement must be accurate at frequencies below nominal, and with a significant rate of change in frequency and voltage decay.



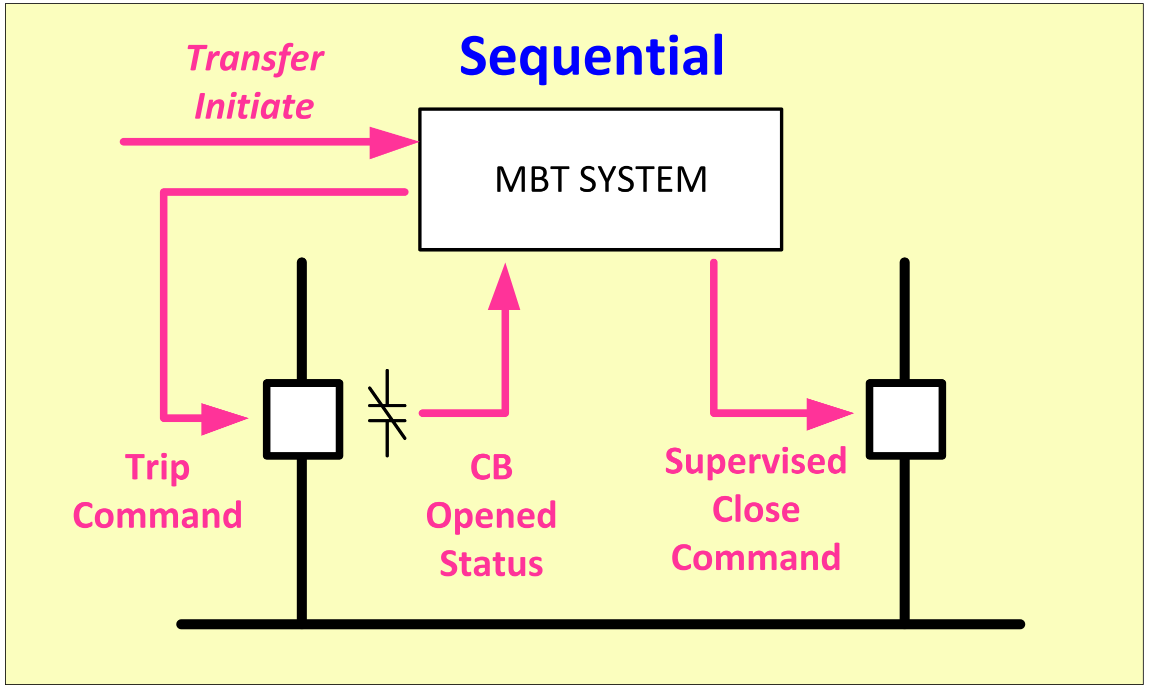
Sync Scope

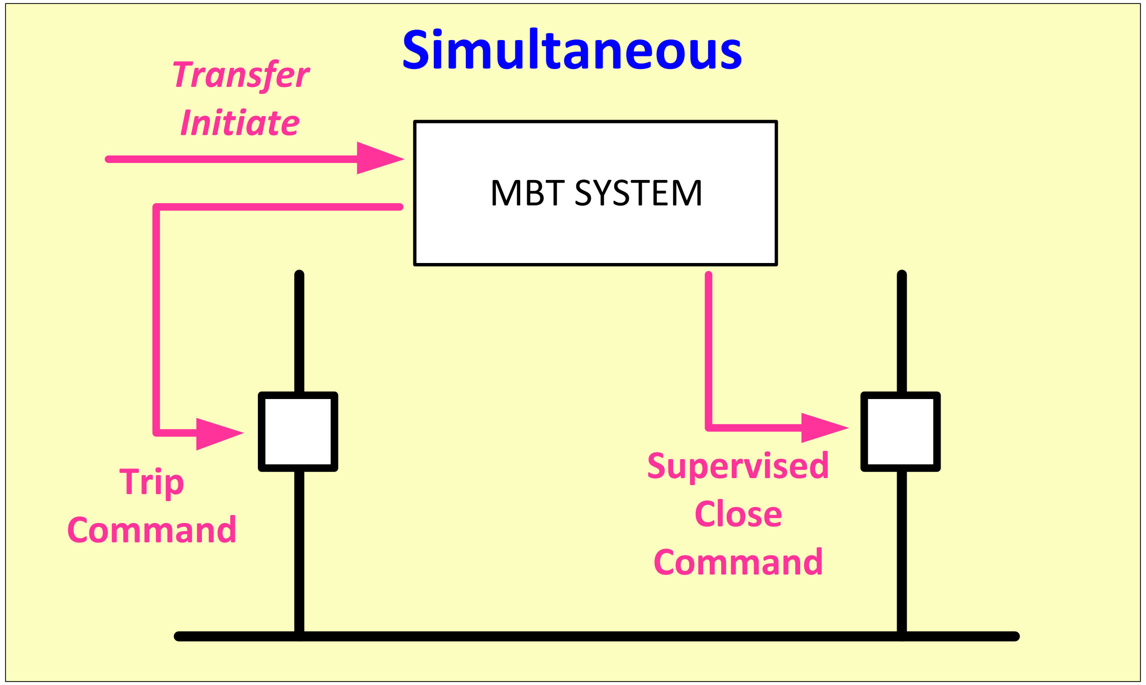
Residual Voltage Transfer Method

Disadvantages

- Very slow; cannot be used for planned transfers during unit startup.
- Transfers must be completed before the bus voltage drops so low that the motor protection undervoltage elements trip the motors.
- If motors are held in with contactors, latching or dc-operated contactors must be used to ensure that the contactors do not drop out.
- Load Shedding may be necessary (causes process interruption):
  - Motor bus frequency may have already decayed past the stall point of motors on the bus.
  - The new source cannot re-accelerate all bus motors simultaneously.
  - Properly sequenced motor restart is then required to prevent excessive voltage dip.
- Motors may undergo high, damaging reconnection torques, which may exceed torques of a three-phase bolted fault.
- **Fast and In-Phase Transfers avoid these issues!**

Open Transition Modes: Sequential & Simultaneous

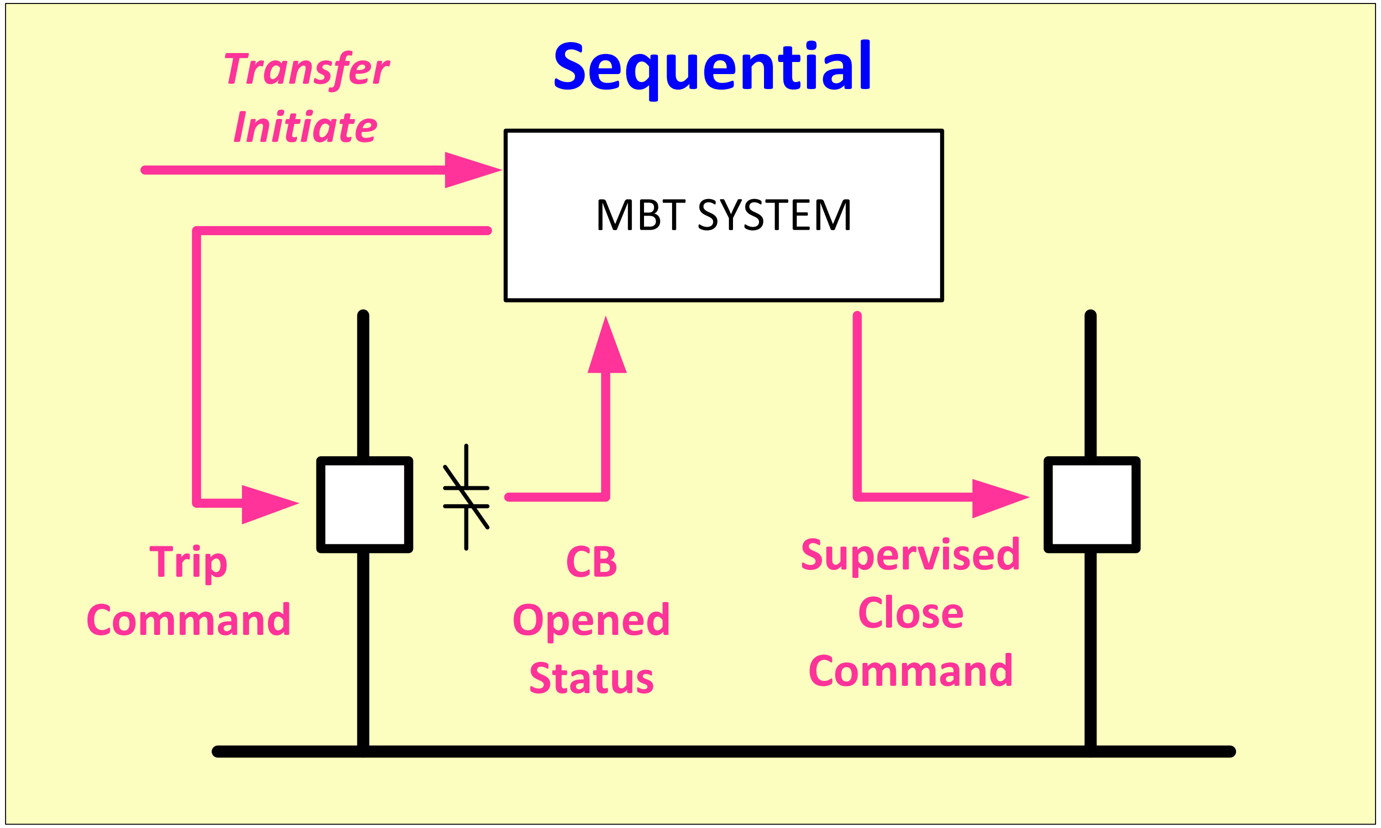




Open Transition: Sequential Mode

- The old source breaker is tripped immediately.
- Closure of the new source breaker is initiated on confirmation by the breaker status contact that the old source breaker has opened.
- Upon receipt of this confirmation, a Fast, In-Phase or Residual Voltage Transfer must be employed to supervise closure of the new source breaker.

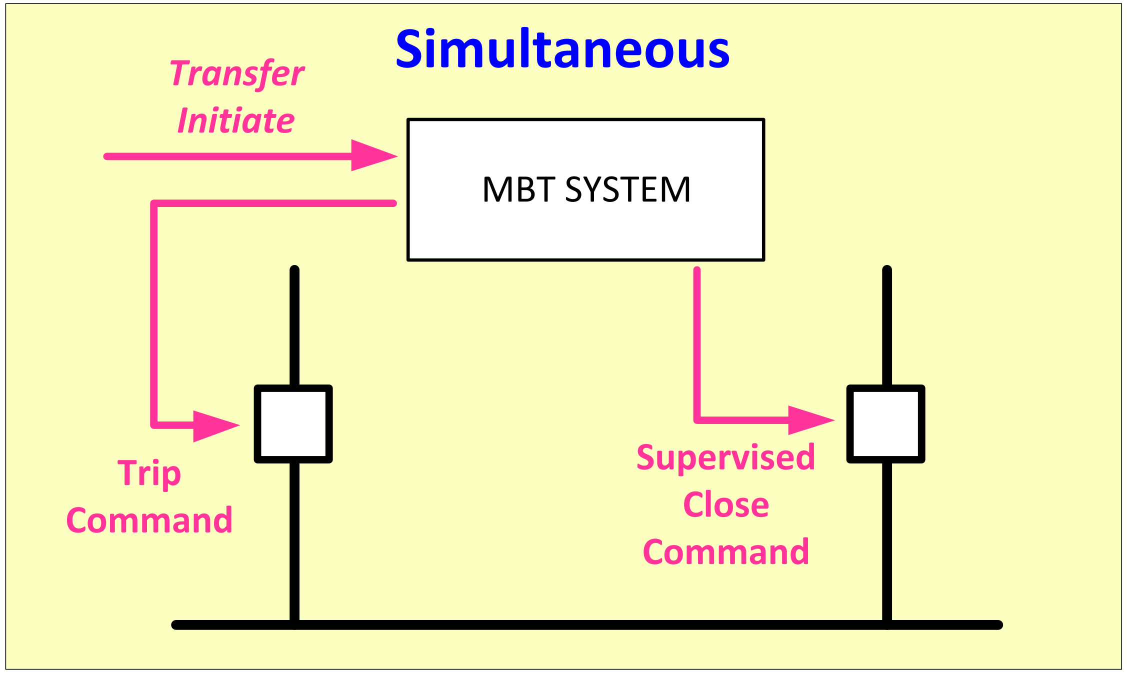
Transfer Timing Sequence



Open Transition: Simultaneous Mode

- Supervised closure of the new source breaker is permitted without waiting for the breaker status contact confirmation that the old source breaker has opened.
- Simultaneous commands are issued for:
  - Old source breaker trip.
  - New source breaker close only if the phase angle between the motor bus and the new source is within the Fast Transfer Phase Angle Limit immediately upon transfer initiate.
- Otherwise, closure of the new source breaker must wait until permitted by the Fast, In-Phase or Residual Voltage Transfer.

Transfer Timing Sequence



Fast Transfer

Sequential Trip of Old and Close of New Sources (uses breaker auxiliary status contact)

Advantages

- Fast.
- Transient torques are reduced due to speed of transfer.
- Transfer of complete bus without interruption of process.
- Prevents parallel transfer operation.
- Prevents parallel transfer upon breaker failure.

Considerations

- Rapid supervision of the phase angle just prior to and just after old source interruption is mandatory and possible with high-speed sync-check relays.
- Presently, the majority of fast transfer systems are NOT correctly supervised by high-speed sync-check relays.

Fast Transfer

Simultaneous Trip and Close of Old and New Sources

Advantages

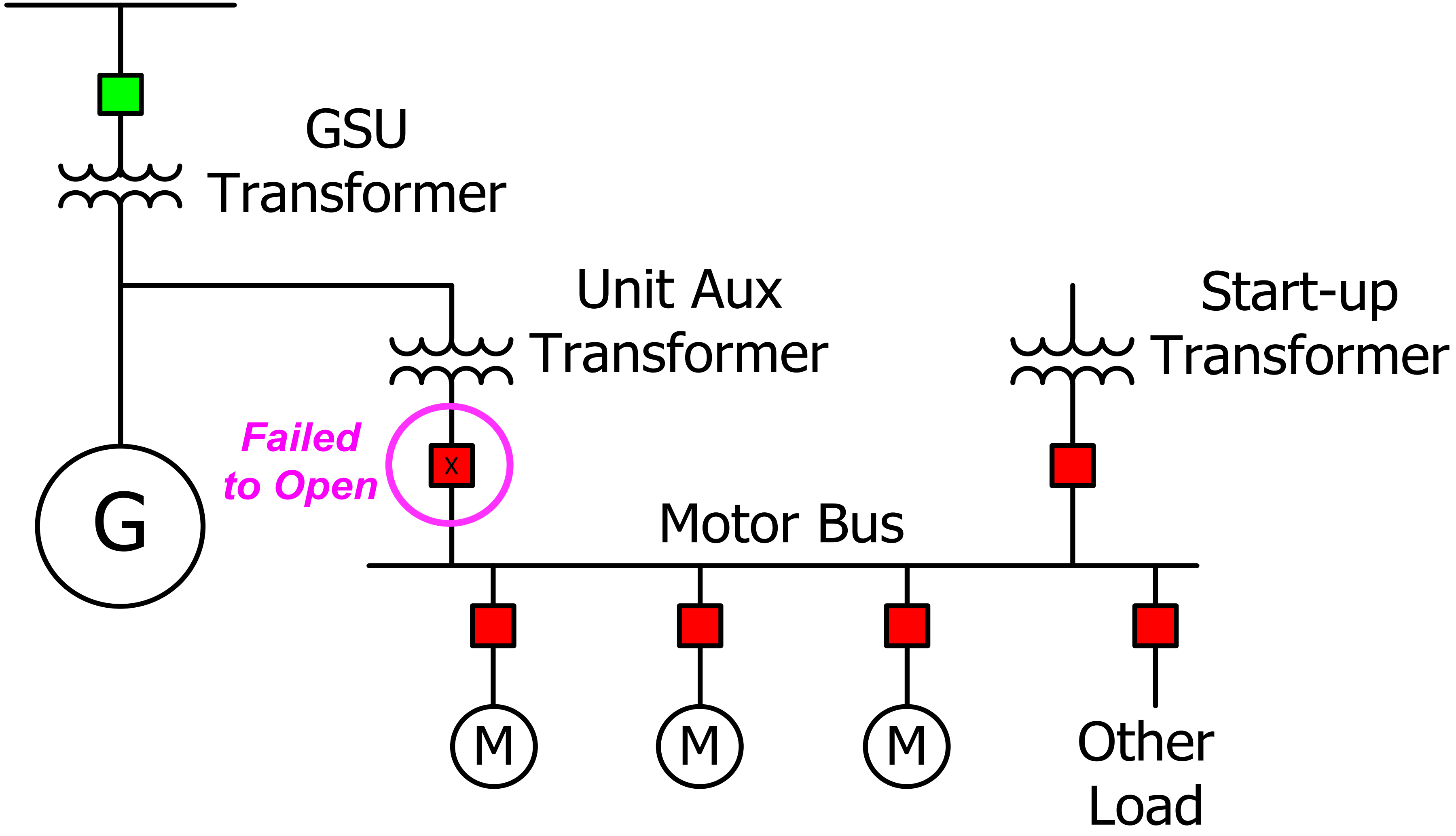
- REALLY Fast - minimum dead time for bus.
- Least exposure to transient torque in motors with minimum interruption of process if system operates properly.

Considerations – Breaker Failure Scheme is a MUST !

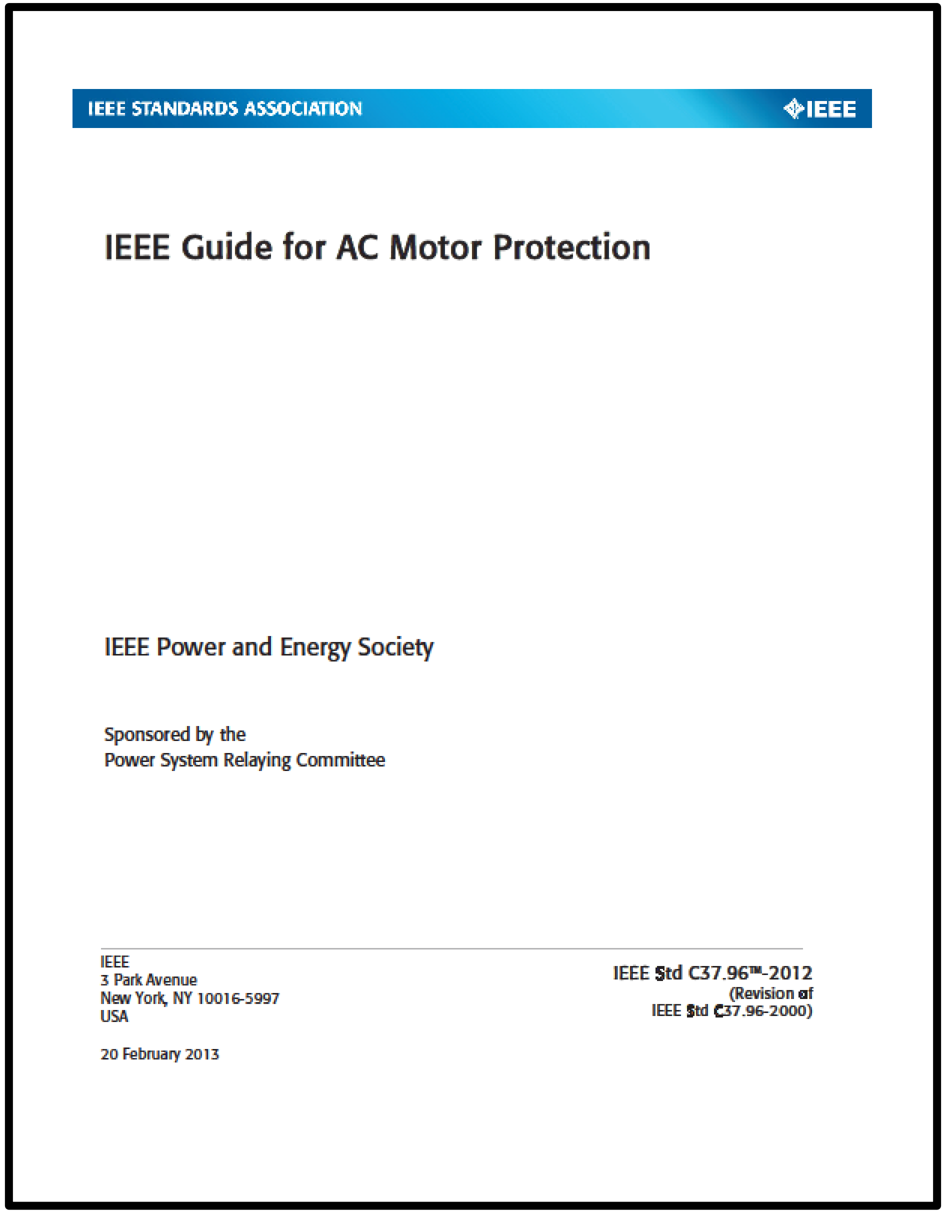
- Rapid supervision of the phase angle just prior to and just after old source interruption is **mandatory** and possible with high-speed sync-check relays.
- Failure of old source breaker to trip requires trip of new beaker just closed:
  - Back feeds generator from new source.
  - Exposes equipment to double-fed faults for which it was not designed.
- Presently, the majority of fast transfer systems are NOT correctly supervised by high-speed sync-check relays.

Open Transition – Simultaneous Mode

Breaker Failure



IEEE Std C37.96-2012 IEEE Guide for AC Motor Protection



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20 February 2013

IEEE Std C37.96™-2012
(Revision of
IEEE Std C37.96-2000)

Excerpts - IEEE Std C37.96-2012

IEEE Guide for AC Motor Protection
Clause 6.4 Motor bus transfer (MBT)

6.4.8 Events that occur or conditions that exist immediately prior to opening the initial source breaker (52-1)

6.4.9.1 Faults on the initial source

…will effect a dynamic change in the phase angle just prior to transfer. It is important that dynamic phase angle changes be recognized by the MBT system.

6.4.9.2 Condition of the alternative source

…determine that the events that triggered the transfer (such as a fault on the initial source) have not also affected the alternate source to the point where it is unsuitable to transfer and continue to supply the motor bus.

6.4.10 Effects of an out-of-step (OOS) generator trip

The 78 relay is typically programmed to trip when the generator’s internal EMF phase is between 120° to 240° relative to the power system. This large internal power angle causes the phase angle across the startup breaker to move to higher-than-expected values… the motor bus voltage will jump quickly to a new phase angle due to the out-of-step angle of the generator internal voltage.

Excerpts - IEEE Std C37.96-2012

6.4.11 System separation between incoming supply sources

6.4.11.1 Different supply voltages

This phase angle difference is caused by supplying the motor bus sources from different voltages… **can result in a substantial voltage phase angle difference between the two sources… load flow characteristics… systems become separated…**

6.4.11.2 Abnormal system operation

The abnormal operation of the power system can **cause a large standing angle between the two sources to the motor bus… the loss of an autotransformer** that ties the systems together… **opening of breakers at a ring bus or breaker-and-a-half substation…**

6.4.11.3 Loading of the supply transformers

The reactive losses that result will cause a voltage phase angle shift between the two sources… **loading of other upstream transformers**… can also affect a phase angle shift.

6.4.12 Supply source transformer winding phase shift

… there could be an inherent phase shift (30°), between the main and alternate source based on the transformer configuration of the two sources.

Takeaway

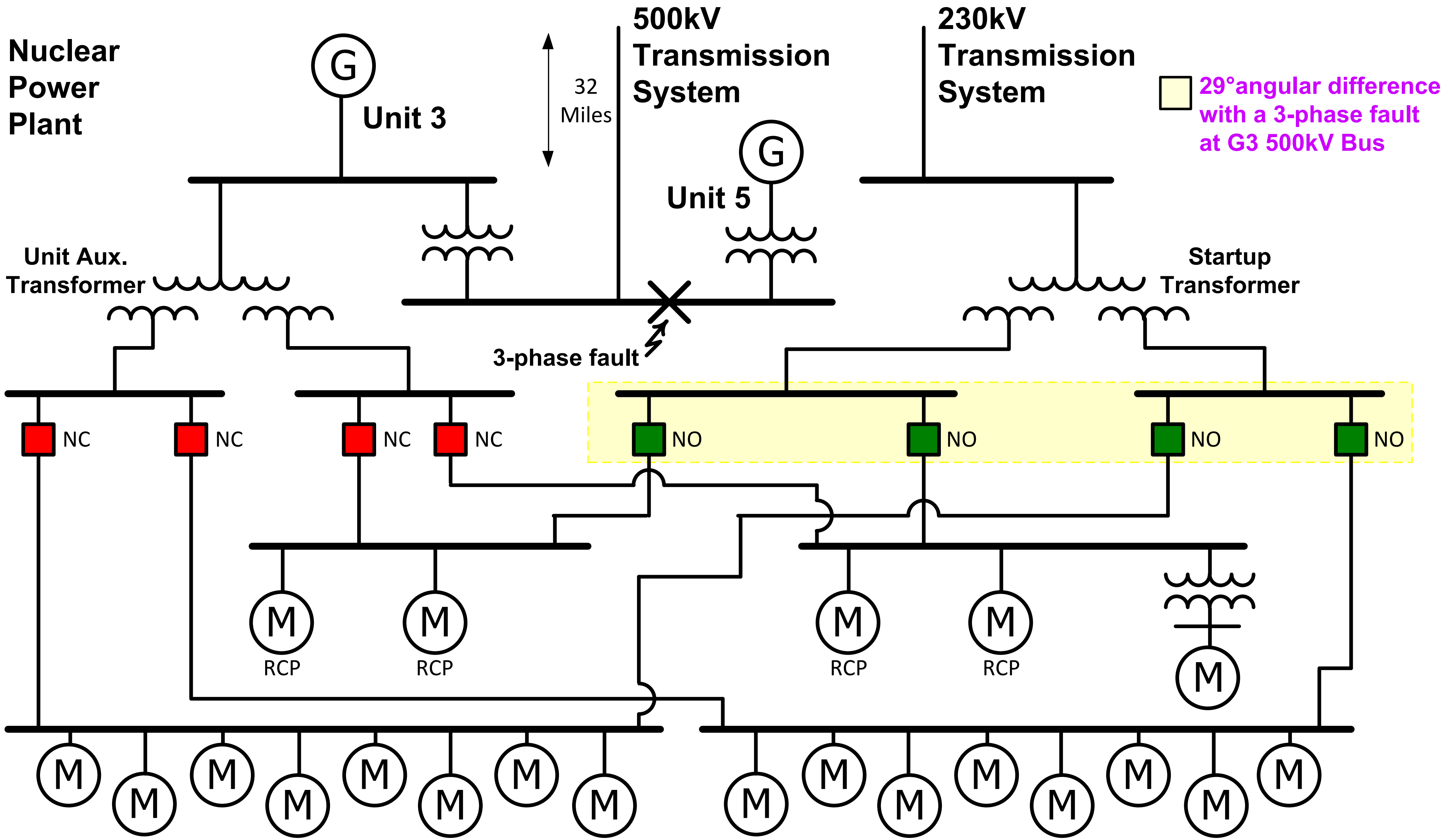
At transfer initiate, the initial phase angle may be nowhere near zero.

6.4.13.1 Transient effects upon disconnection of motor loads

… the characteristic of induction motors whereby they exhibit an **essentially instantaneous phase shift upon disconnect of motor**… This effect is additive to conditions occurring due to other causes…

ANSI/NEMA STANDARD C50.41-2012
Polyphase Induction Motors for Power Generating Stations
clause 14.3 states, “test conditions should account for any phase angle difference between the incoming and running power supplies.”

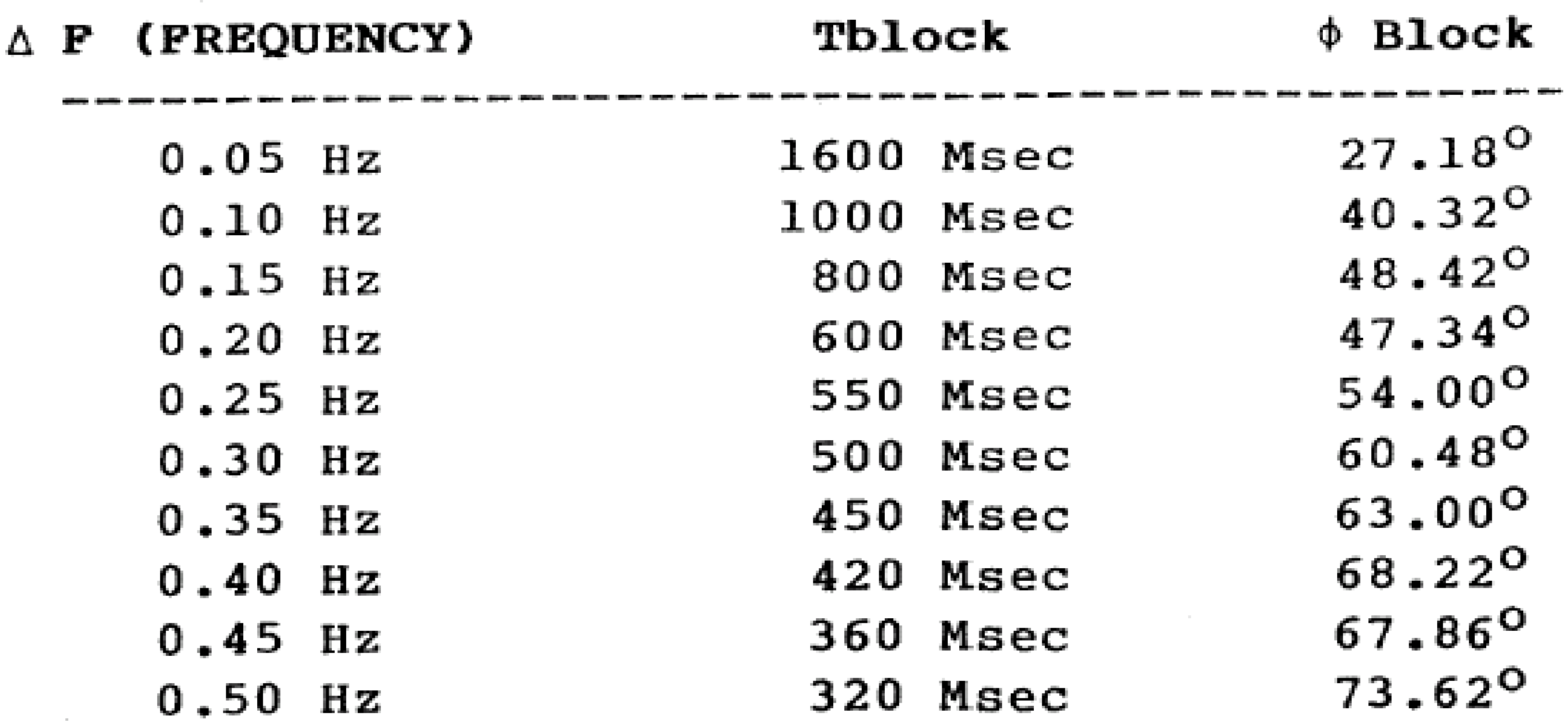
Nuclear Power Plant



☐ 29°angular difference with a 3-phase fault at G3 500kV Bus

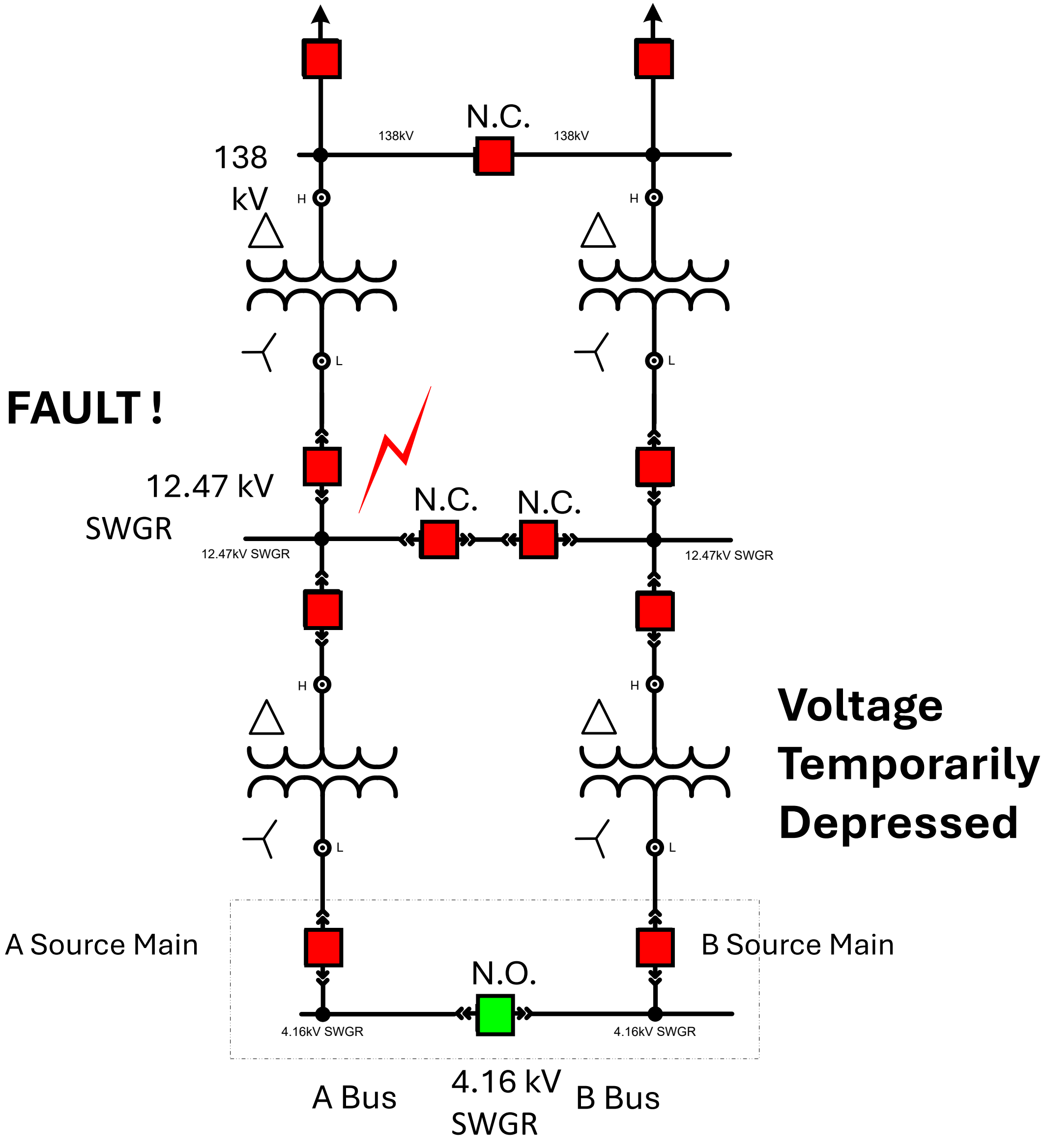
Electromechanical Synchronism-Check Relay Test

- The purpose of this test was to determine the blocking characteristics of an E/M Relay set for 20° and minimum time delay.
- With the initial phase angle at 0° and both inputs at 60Hz, increase the line frequency to create a slip frequency (∆F) and measure the blocking time and blocking angle.
- Tests were run for the following conditions:
  - **TEST DATA**



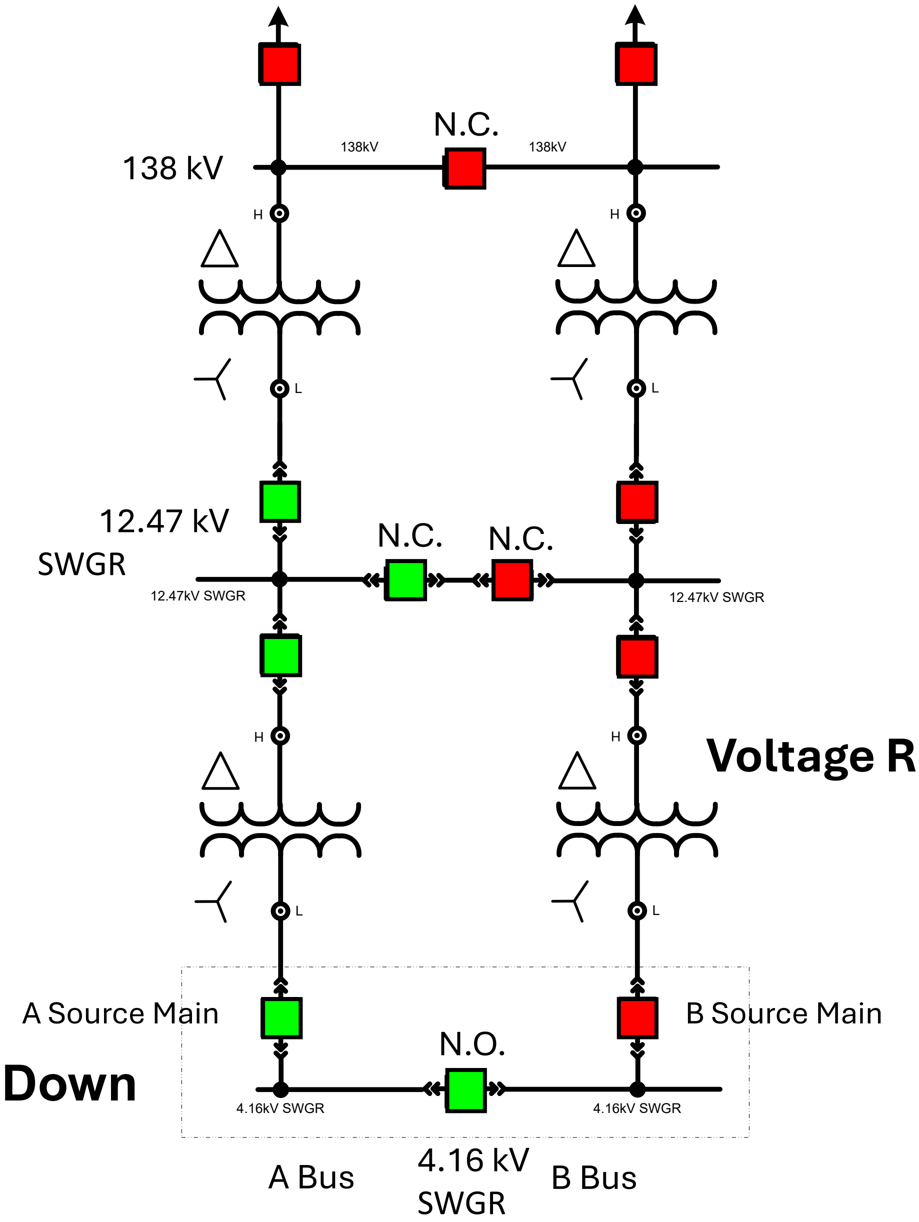
∆ F (FREQUENCY)	Tblock	ϕ Block
0.05 Hz	1600 Msec	27.18°
0.10 Hz	1000 Msec	40.32°
0.15 Hz	800 Msec	48.42°
0.20 Hz	600 Msec	47.34°
0.25 Hz	550 Msec	54.00°
0.30 Hz	500 Msec	60.48°
0.35 Hz	450 Msec	63.00°
0.40 Hz	420 Msec	68.22°
0.45 Hz	360 Msec	67.86°
0.50 Hz	320 Msec	73.62°

Industrial Redundant Incoming Source



Voltage Temporarily Depressed

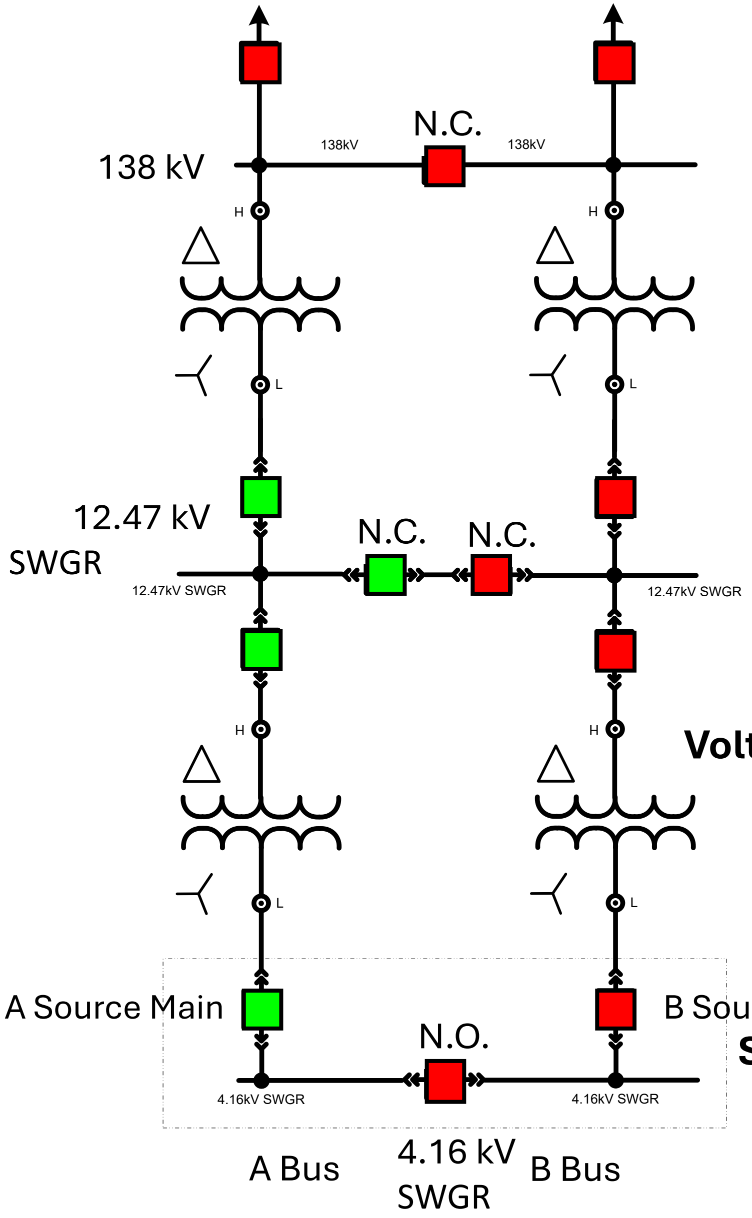
Industrial Redundant Incoming Source



Voltage Recovering

Motors Spinning Down

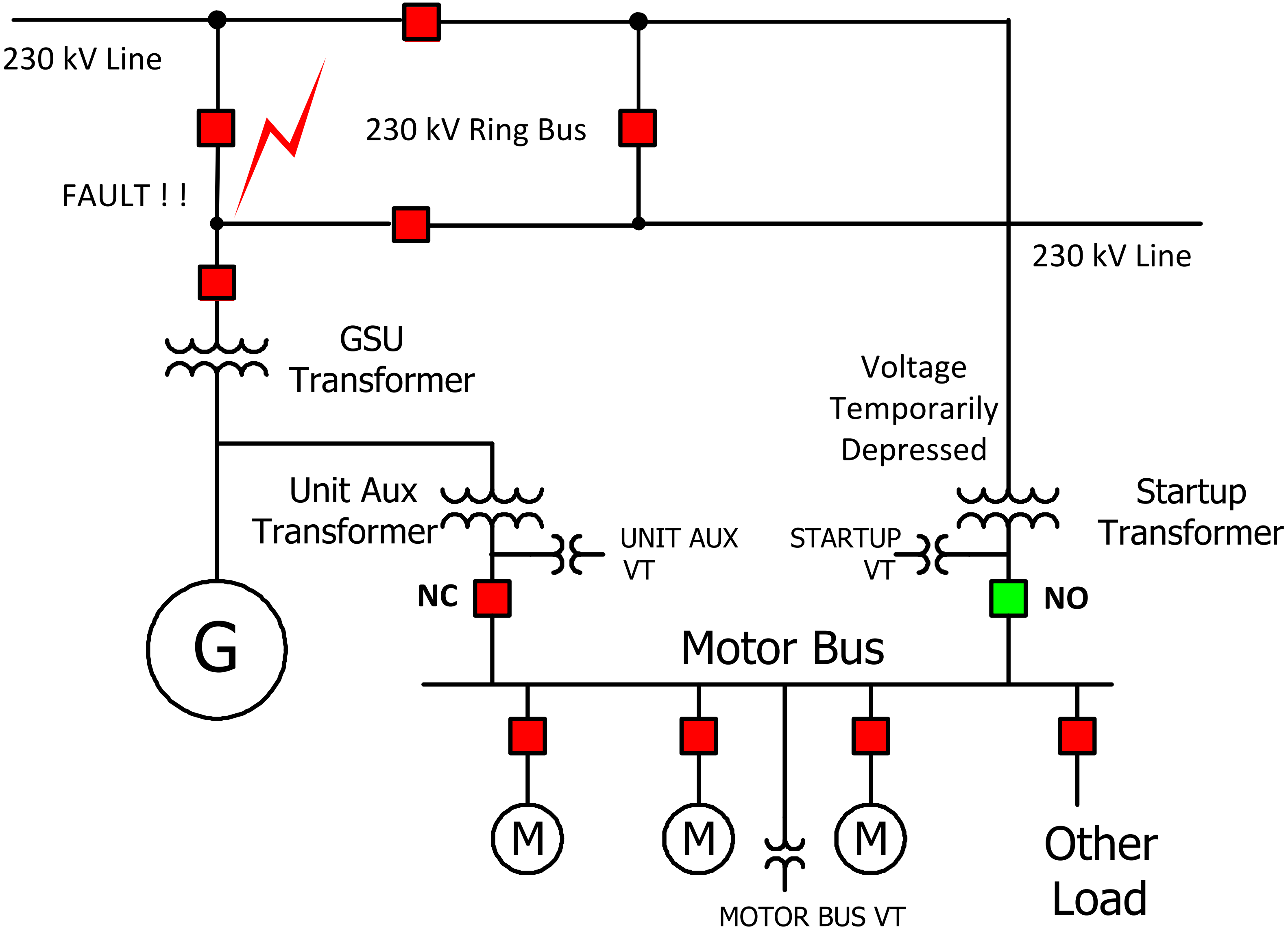
Industrial Redundant Incoming Source



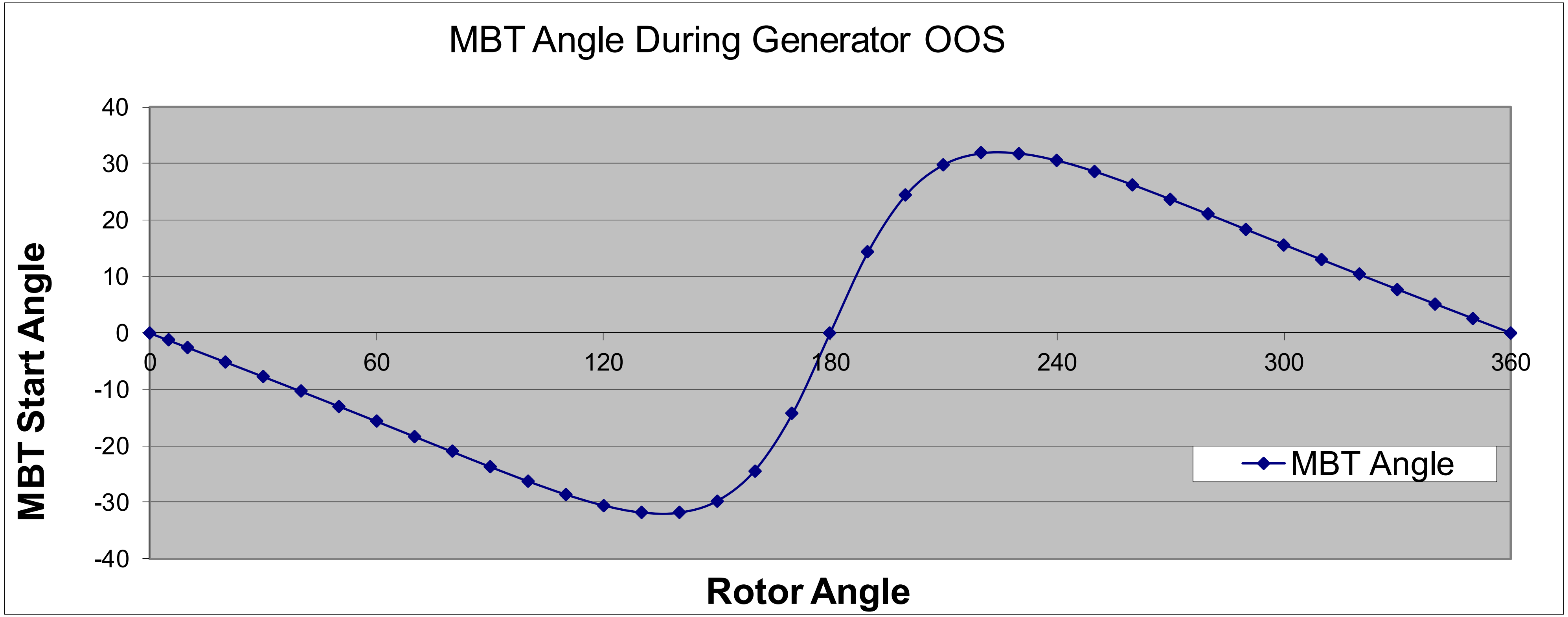
Voltage Recovers

SYNCHRONOUS TRANSFER COMPLETED

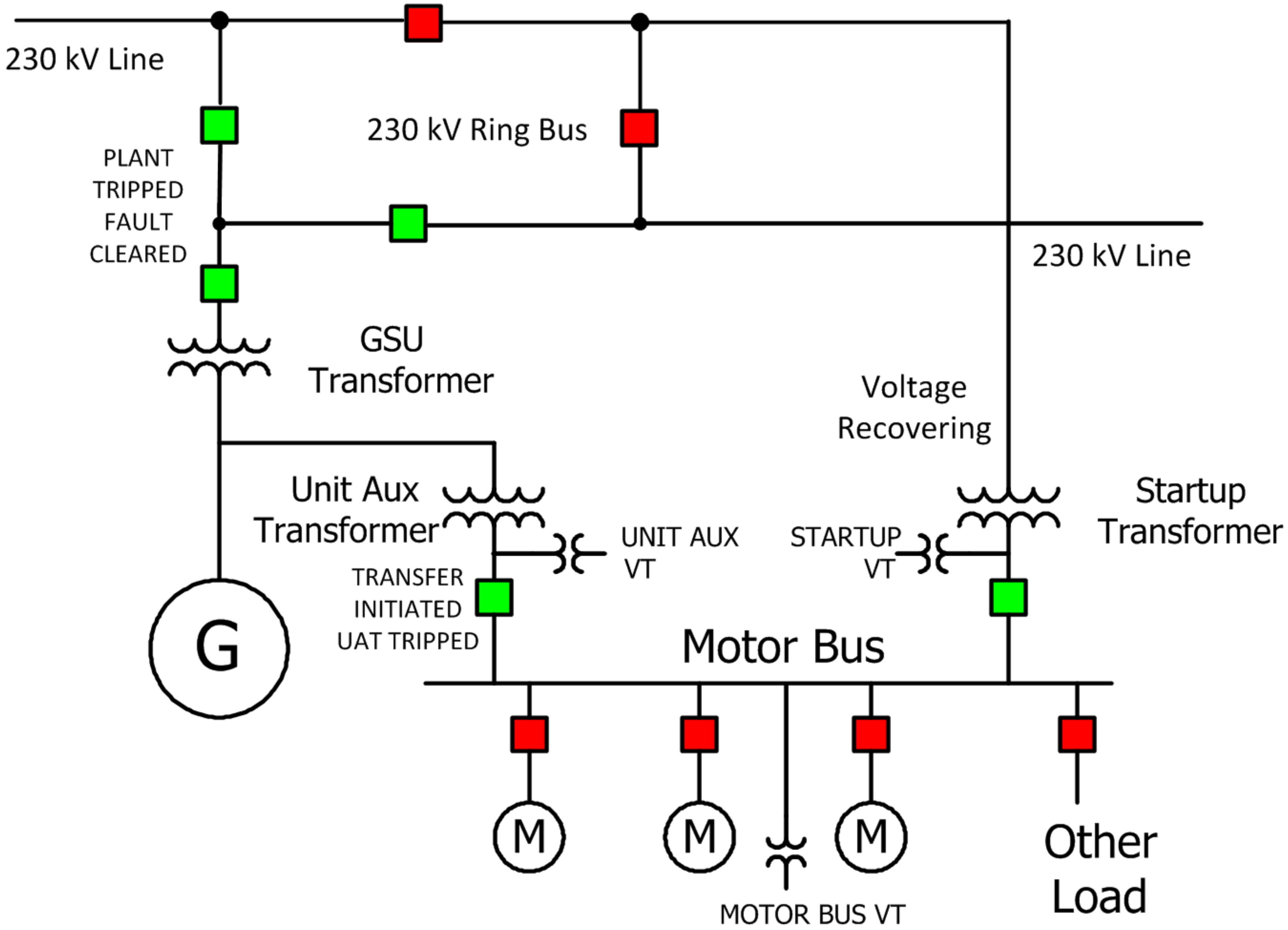
Fault at Generating Station



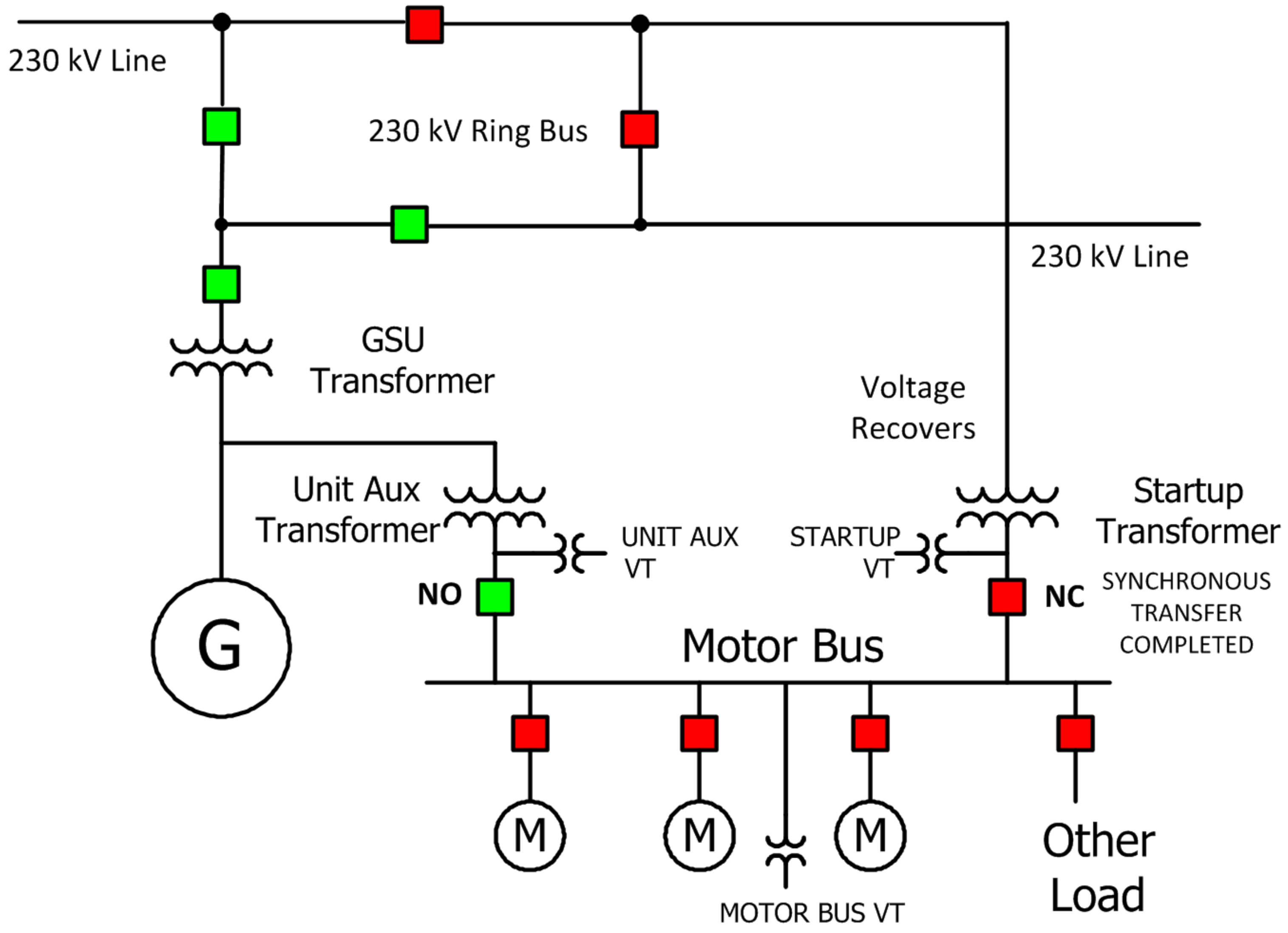
MBT Angle During Generator OOS



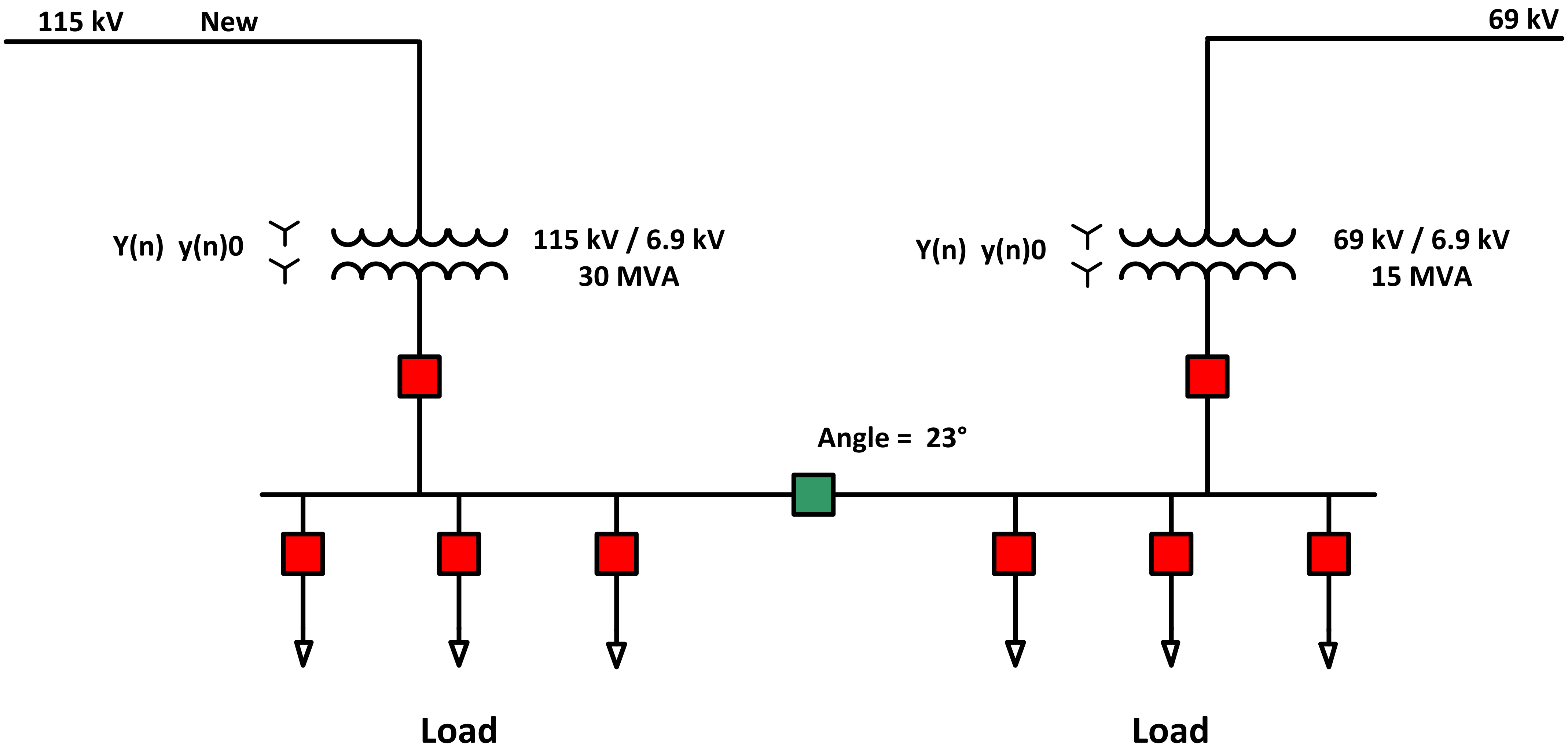
Fault at Generating Station



Fault at Generating Station

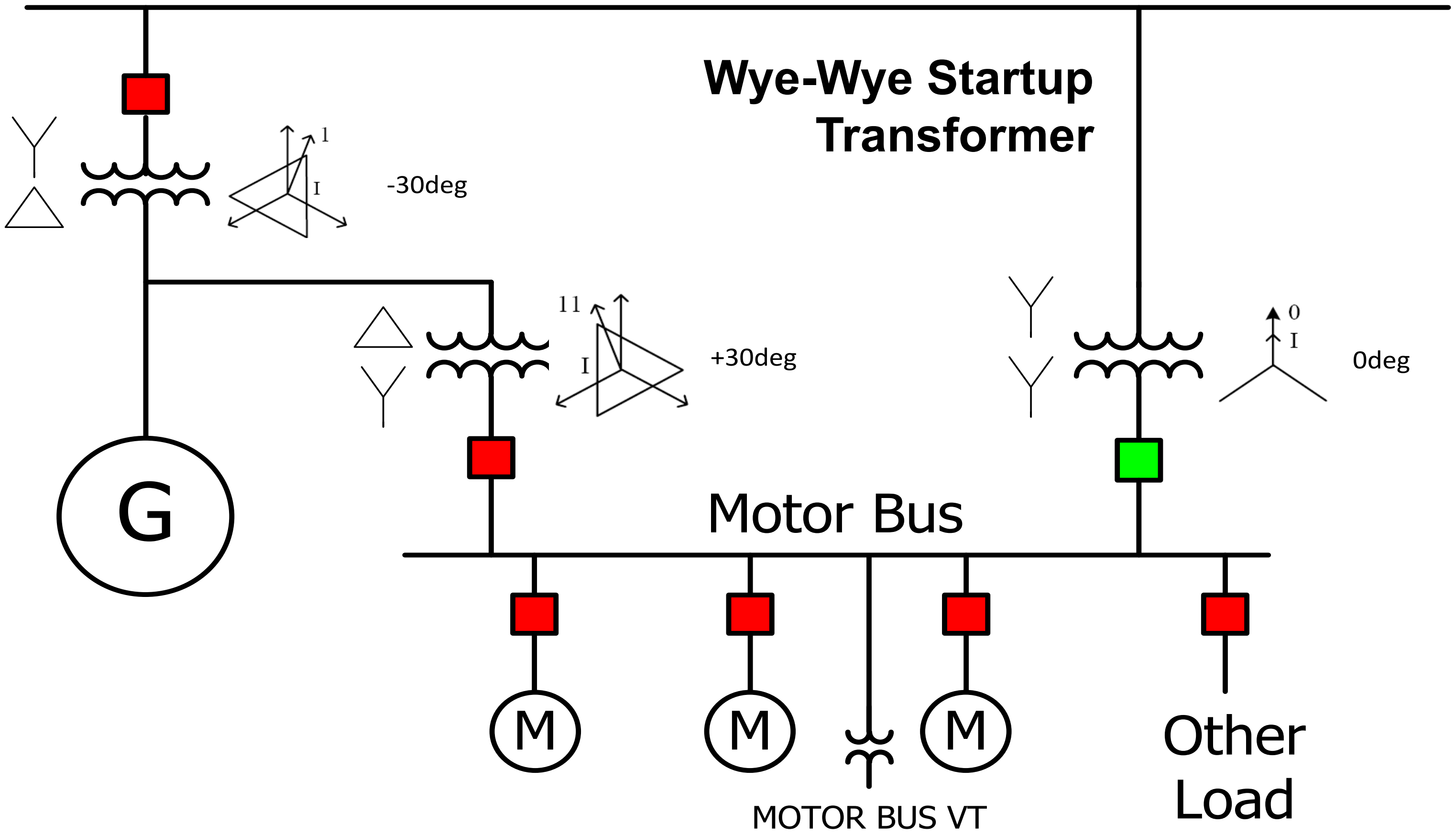


Petrochemical Plant



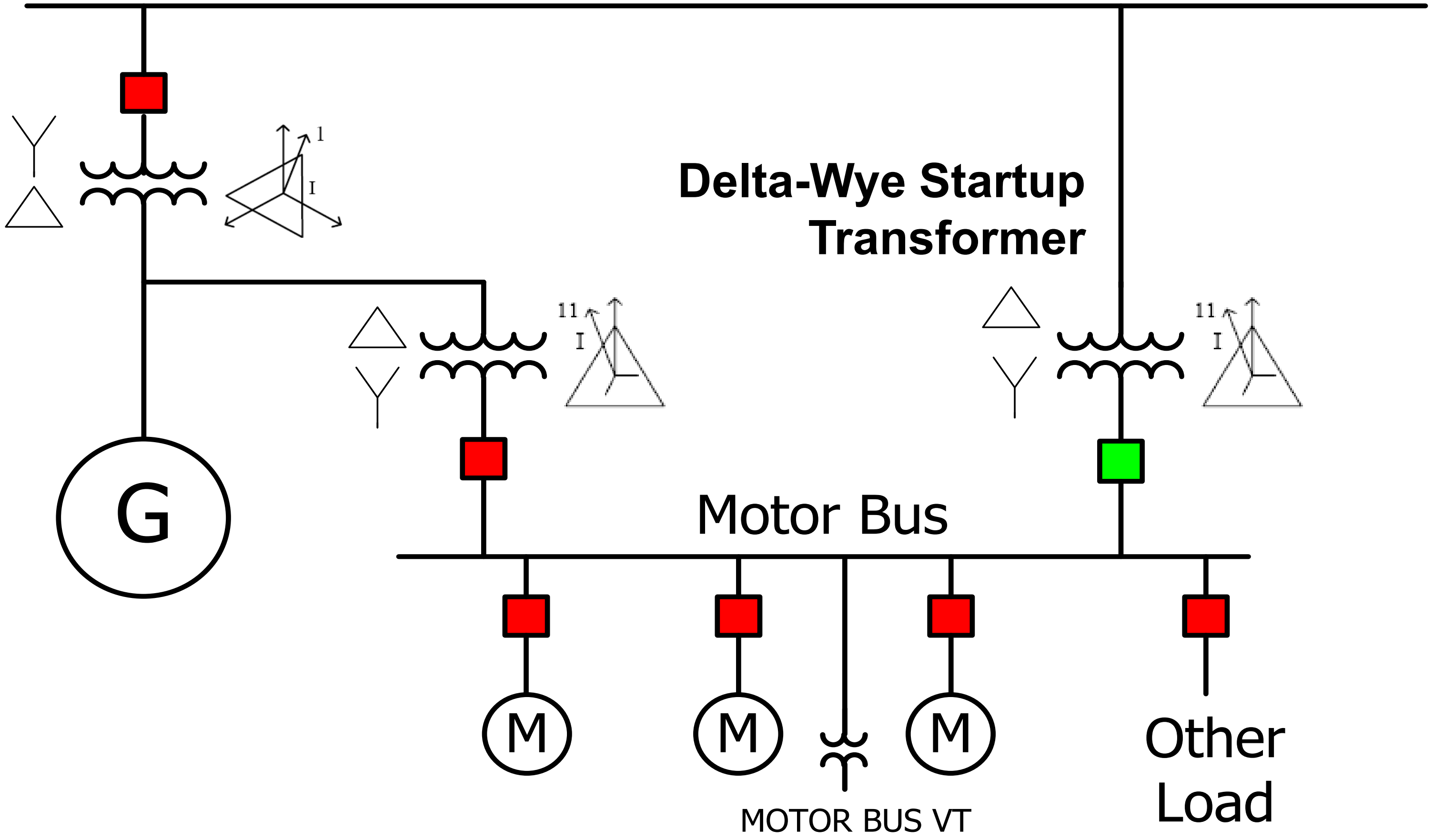
Unit-Connected Generator Motor Bus

- In typical applications, a wye-wye or delta-delta Startup Transformer connection is used, resulting in a net phase shift of 0° between the Unit Auxiliary and Startup Transformers.
- In this case Hot Parallel Transfers are possible and Open Transition Fast Transfers are permitted given sufficiently fast sync check supervision and breaker speeds.



Unit-Connected Generator Motor Bus

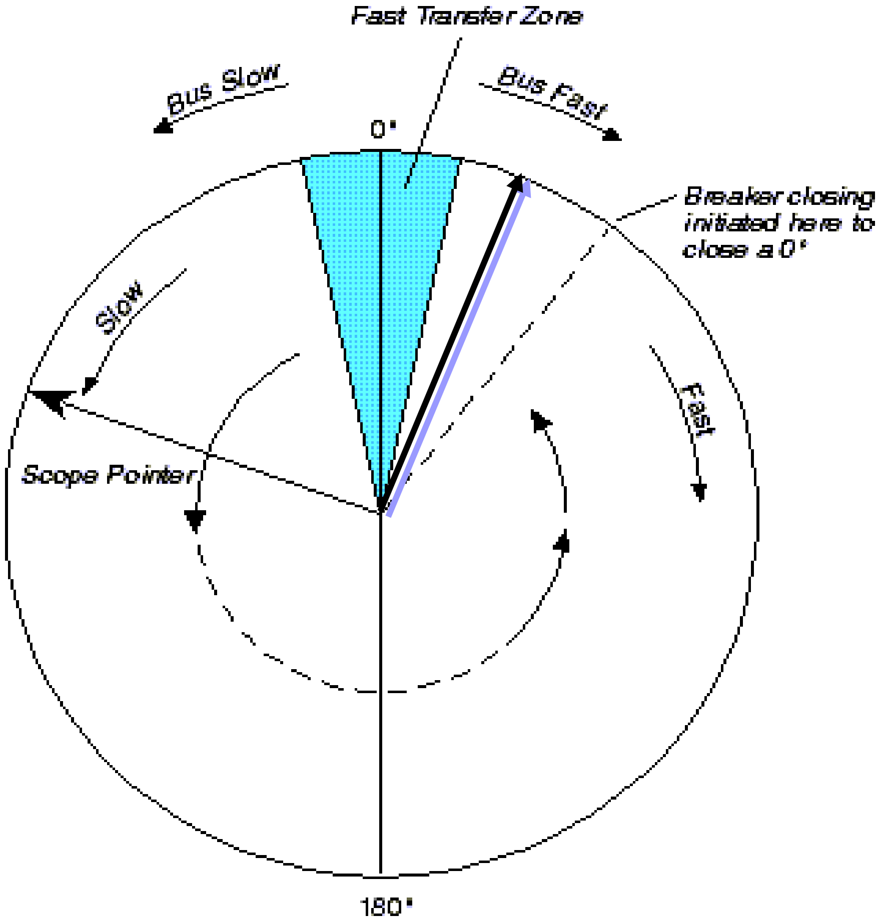
- In some plants, a delta-wye Startup Transformer has been specified, creating a 30° phase shift between the Unit Auxiliary and Startup Transformers.
- In this case Hot Parallel Transfers are **<u>NOT</u>** possible and Open Transition Fast Transfers are permitted given sufficiently fast sync check supervision and breaker speeds.



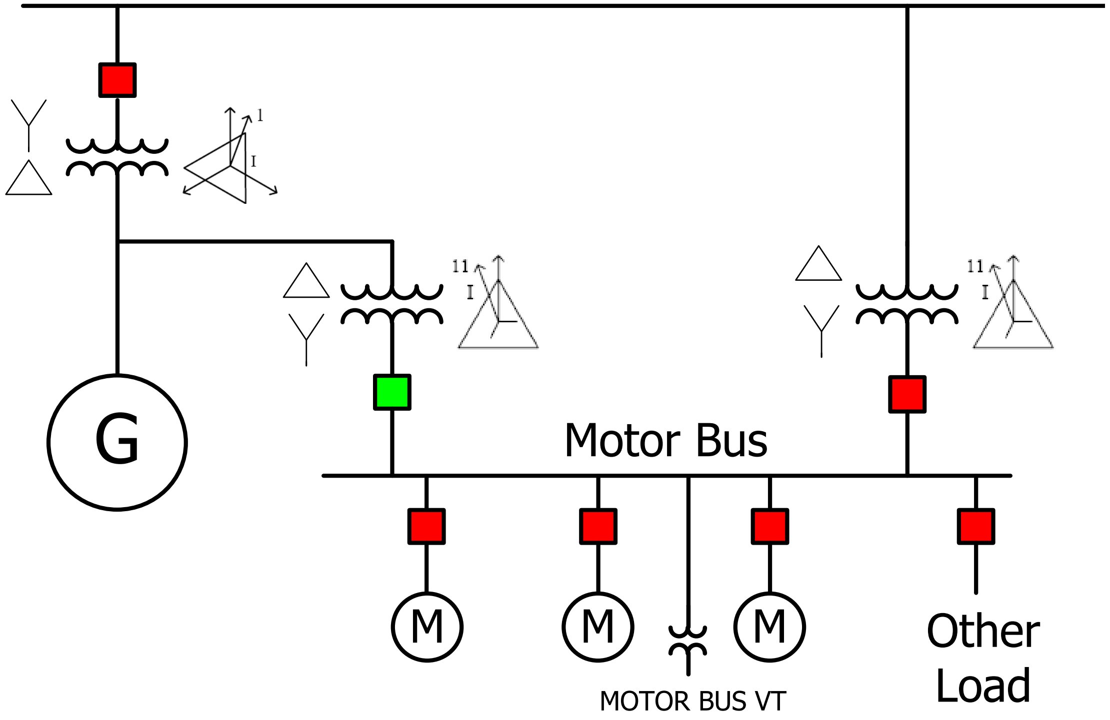
Unit-Connected Generator Motor Bus

Startup to Unit Aux Transfer

Fast Transfer Possibility with Hi-Speed Sync Check



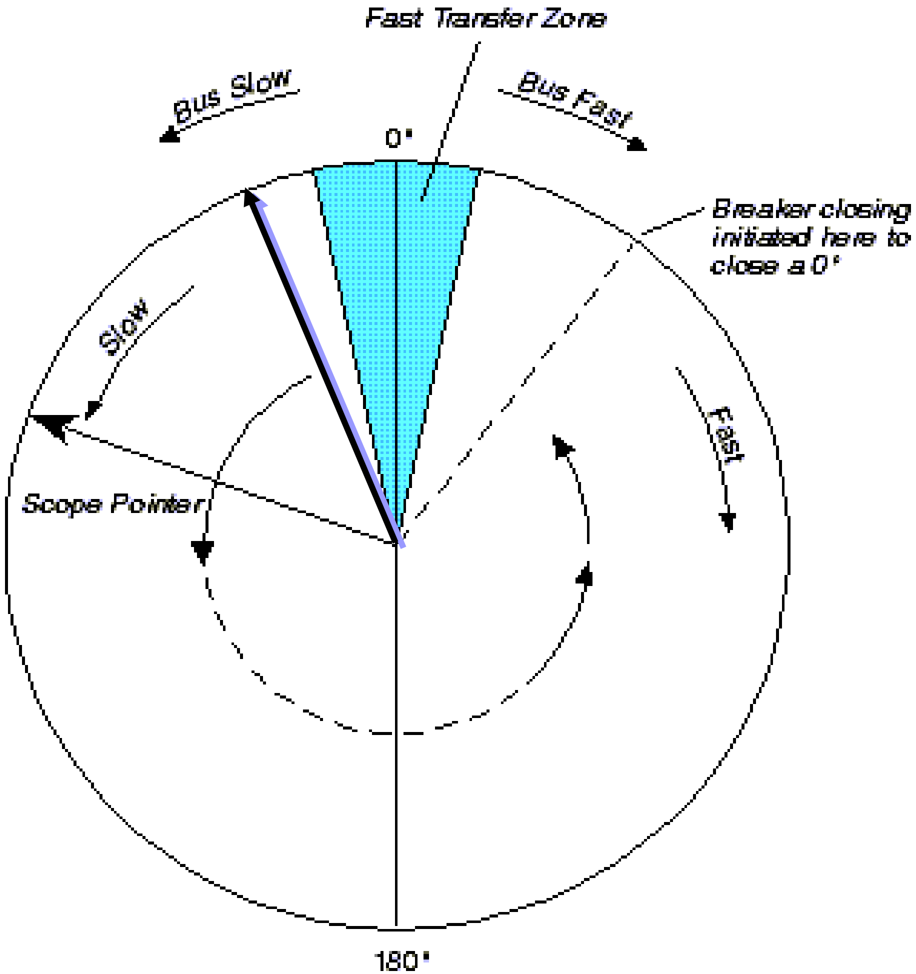
- The Startup Transformer source leads the Unit Auxiliary Transformer source by 30 deg.
- Hot parallel transfers are NOT possible.
- After the Startup Transformer breaker opens, the Motor Bus will begin rotating in the slow direct which moves the Bus voltage towards the Unit Aux Transformer voltage.



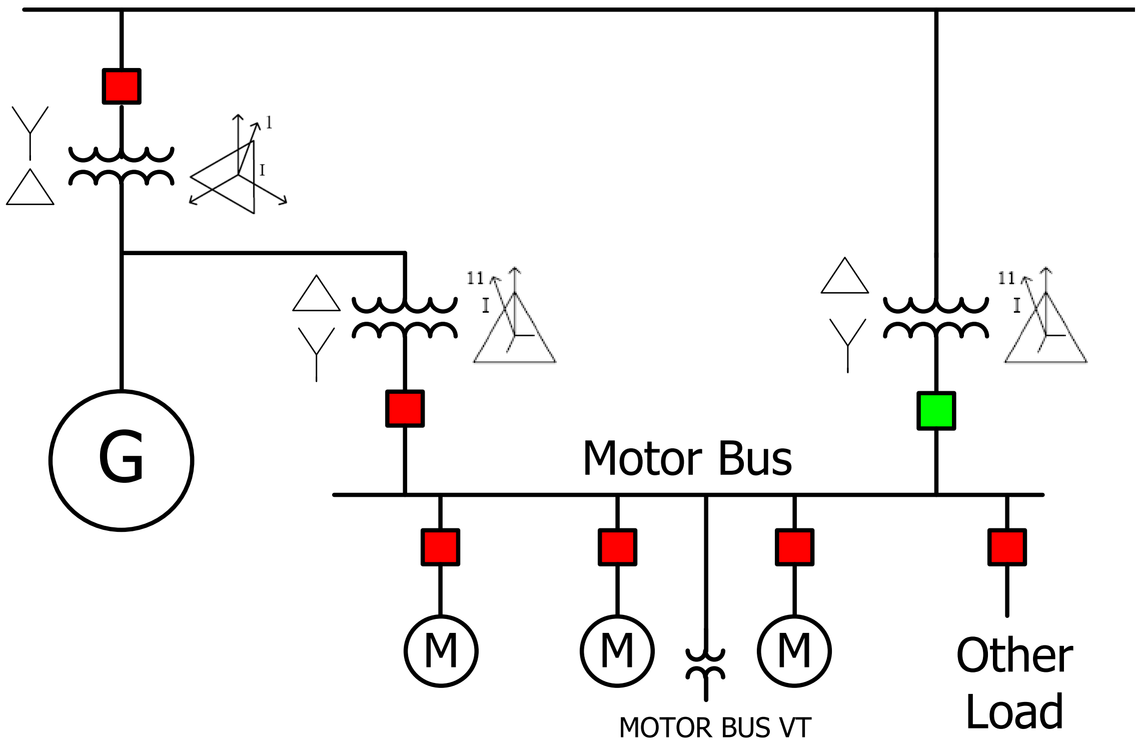
Unit-Connected Generator Motor Bus

Unit Aux to Startup Transfer

In-Phase Transfer Possibility



- The Unit Auxiliary Transformer source lags the Startup Transformer source by 30°.
- After the Unit Auxiliary Transformer breaker opens, the Motor Bus will begin rotating in the slow direct which moves the Bus voltage away from the Startup Transformer voltage.

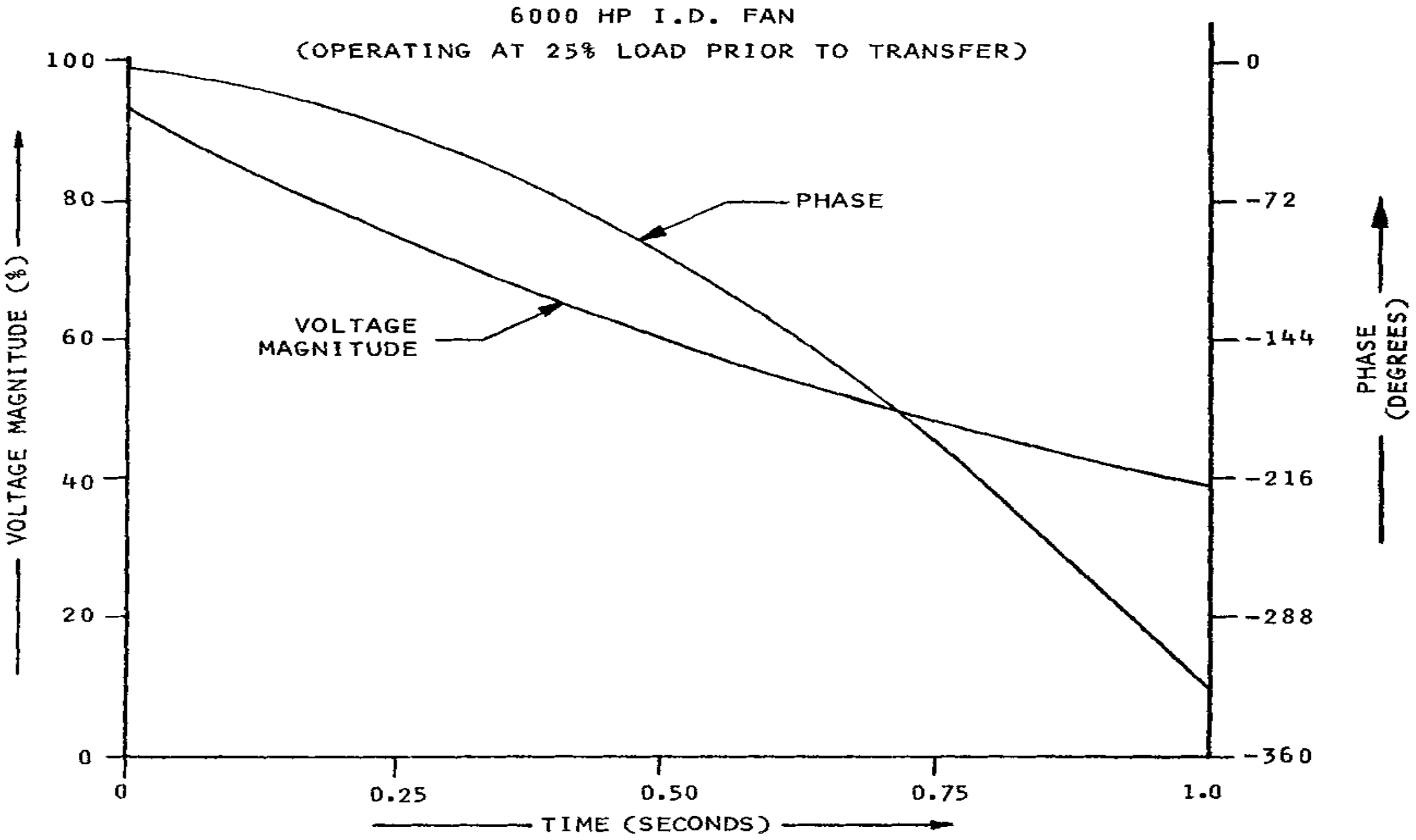


Transient Effects upon Disconnect of Motor Loads

- Essentially instantaneous phase shift upon disconnect of Motor.
  - Simulation based on 7,860 hp Induction Motor operating at full load supplied from 11,550 VAC bus.
  - Instantaneous phase shift of 9 to 10 degrees in the slow direction calculated upon disconnect.
  - Effect is additive to conditions occurring due to other causes.
  - Effect is followed by subsequent frequency decay, the speed of which is dependent on inertia and loading of motor.
- Same effect occurs upon disconnect subsequent to a bus fault.

Phase Angle and Motor Bus Voltage Characteristics

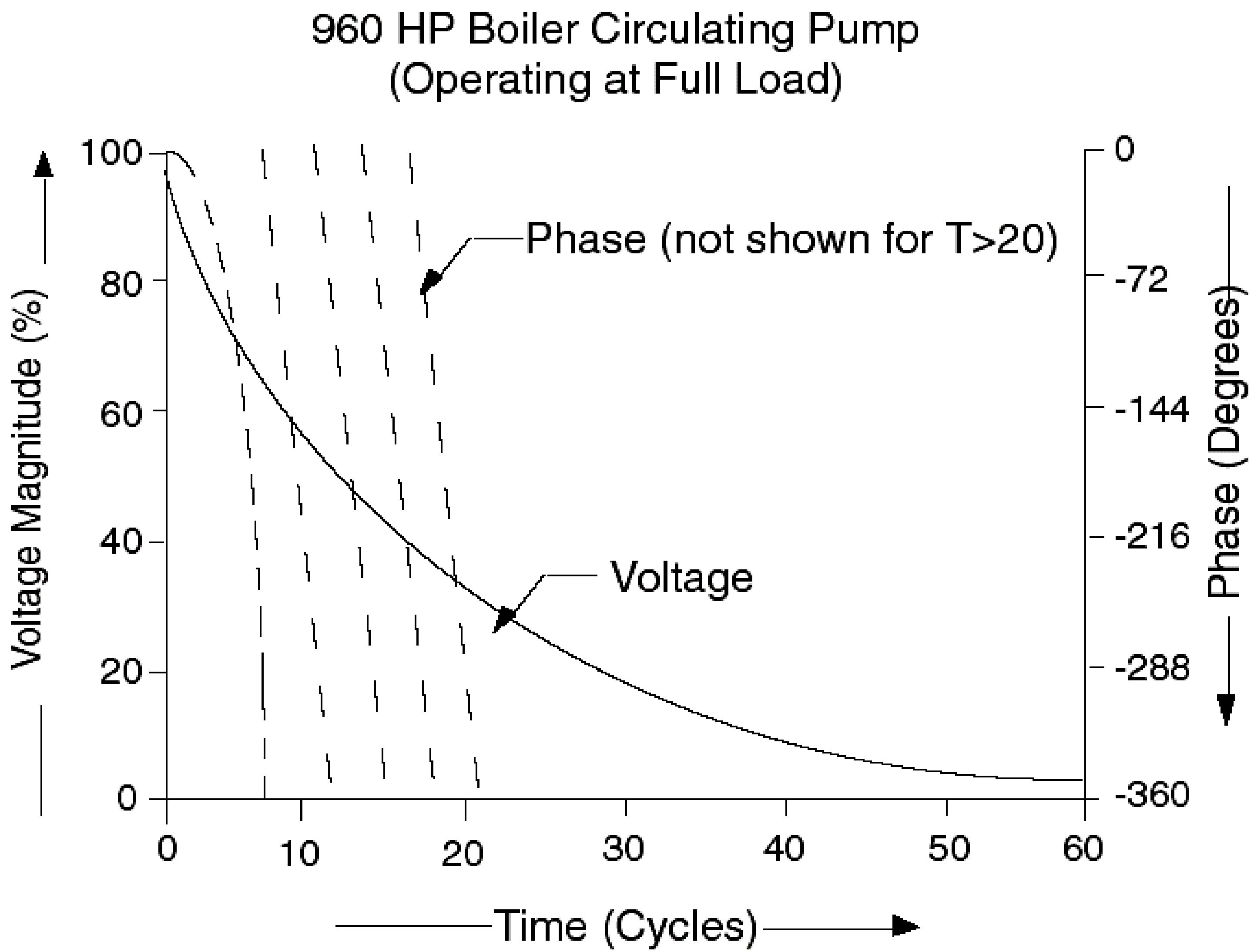
High Inertia Motor/Load



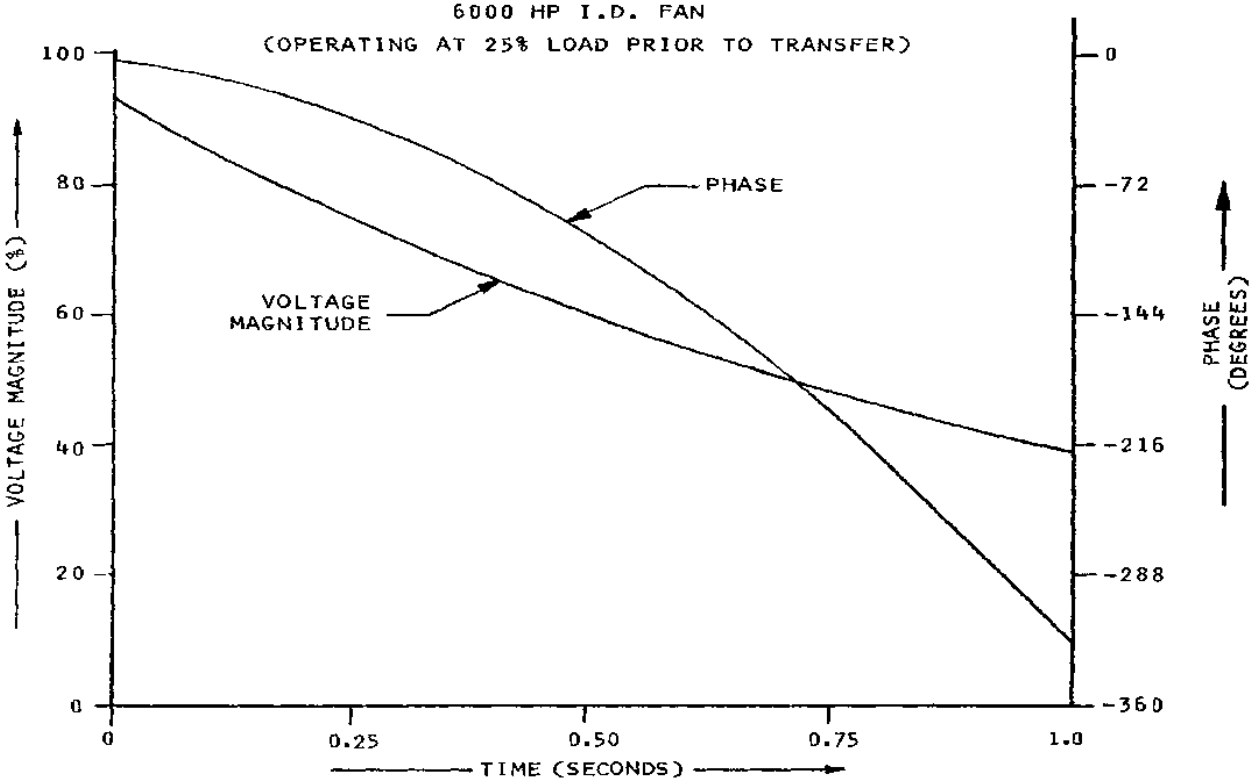
Phase angle rate of change (caused by deceleration of the motors during transfer) and the rate of voltage decay determined by the type of motors in use and the type of loads being driven.

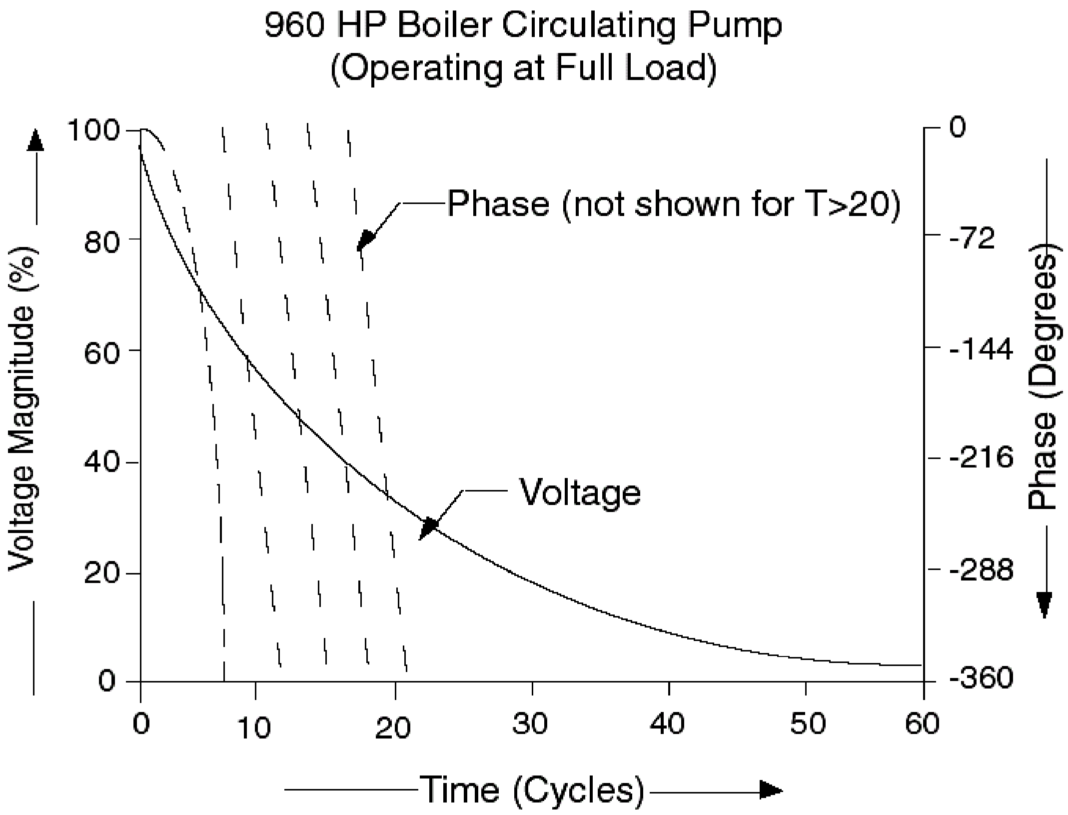
Phase Angle and Motor Bus Voltage Characteristics

Low Inertia Motor/Load



Effect of Motor/Load Inertia


6000 HP I.D. FAN
(OPERATING AT 25% LOAD PRIOR TO TRANSFER)


960 HP Boiler Circulating Pump
(Operating at Full Load)

High inertia loads tend to hold up motor buses.

Motors on a bus create a composite decay characteristic.

Motor & Load Characteristics: Effects on MBT

- Motor Size: The larger the motor, the longer the time the voltage will take to decay on an induction motor.
- Loading: The higher the load on the motors, the faster the motor bus frequency will decay.
- 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 coast down 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 motor bus decays quickly, and the slip frequency between the motor bus and the new source quickly increases.

Motor & Load Characteristics: Effects on MBT

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.

Transfer Initiate

NOTE: For each of the following, transfers may be bi-directional or may be programmed to only transfer in one direction.

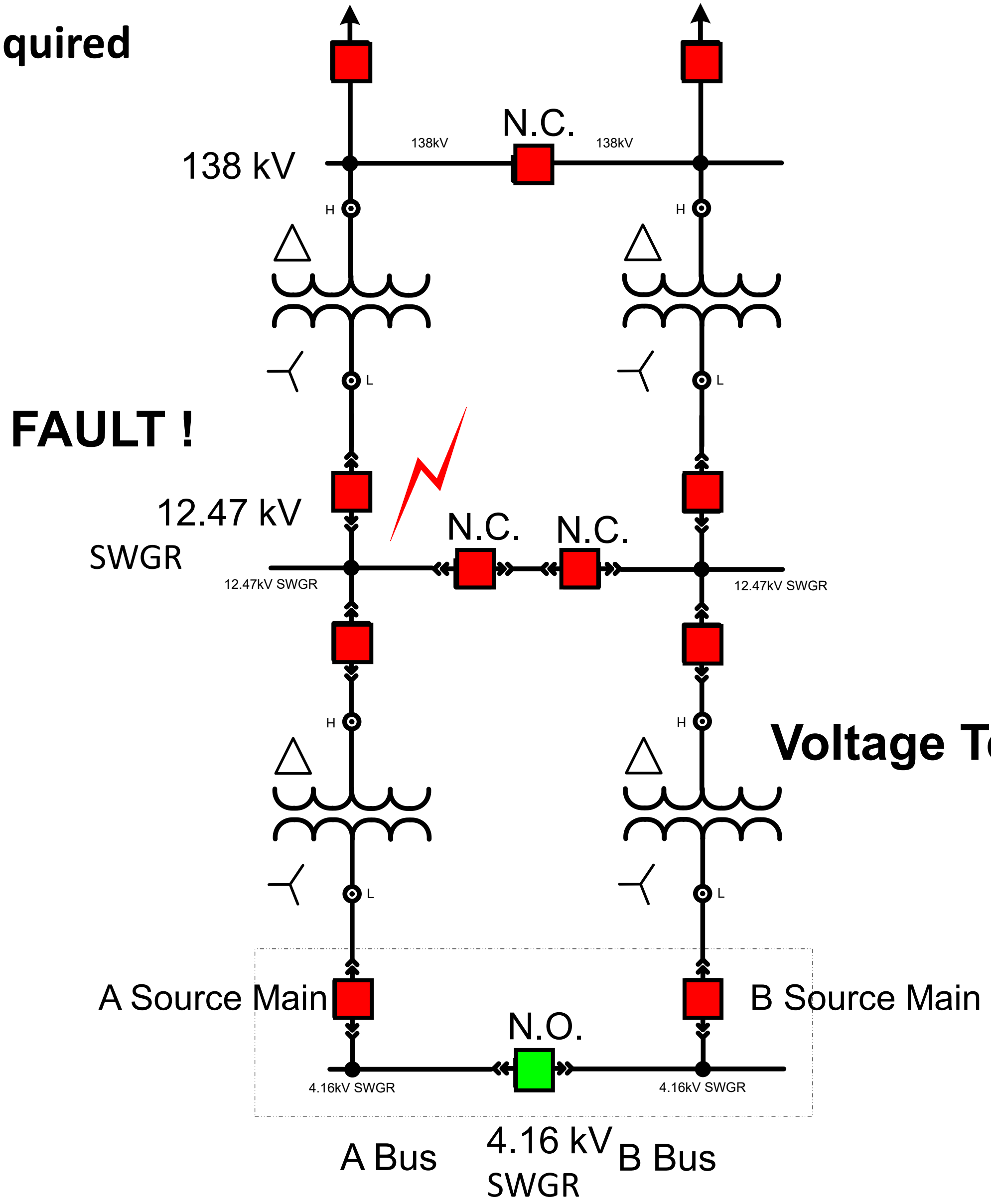
- Protective Relay Initiate must come from ALL relay operations that would remove power from motor bus sources.
- External Initiate
- Auto Transfer Initiate on Bus Undervoltage
  When enabled, this automatically initiates transfer whenever the motor bus voltage drops below an under voltage limit for a set time delay. MUST be set to ride through normal bus voltage dips.
- Both Breakers Open: Auto Close Initiate or Block Transfer
  If both breakers are detected in the open state, due to an external operation that opens the old source breaker while leaving the new source breaker open, an Open Transition, Sequential Mode Transfer can be initiated to close the new source breaker.
- Manual Initiate
  - Local or Remote
  - Selectable for Open Transition or Closed Transition Transfers

Motor Bus Transfer

Transfer Initiate… or Not And Why

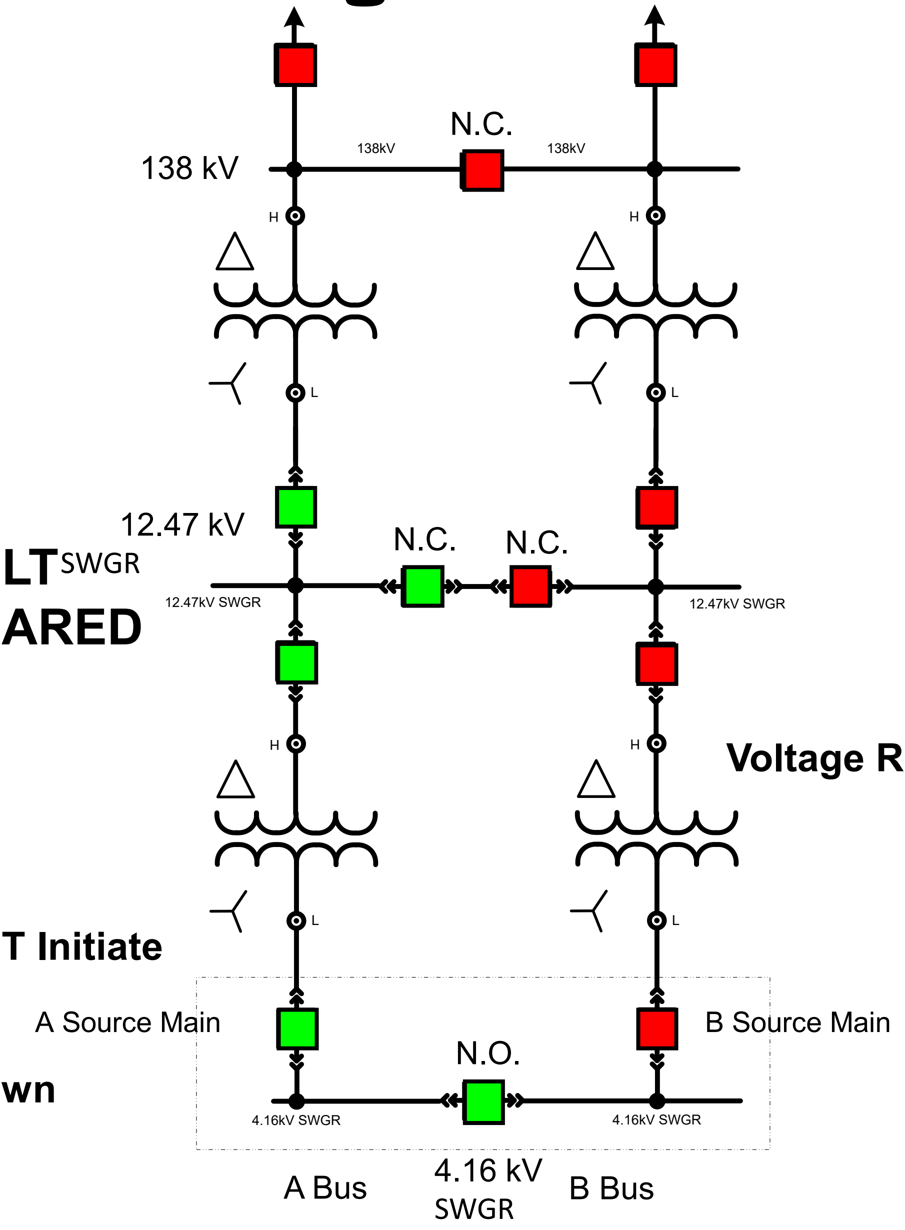
Industrial Redundant Incoming Source

Motor Bus Transfer Initiate Required



Voltage Temporarily Depressed

Industrial Redundant Incoming Source



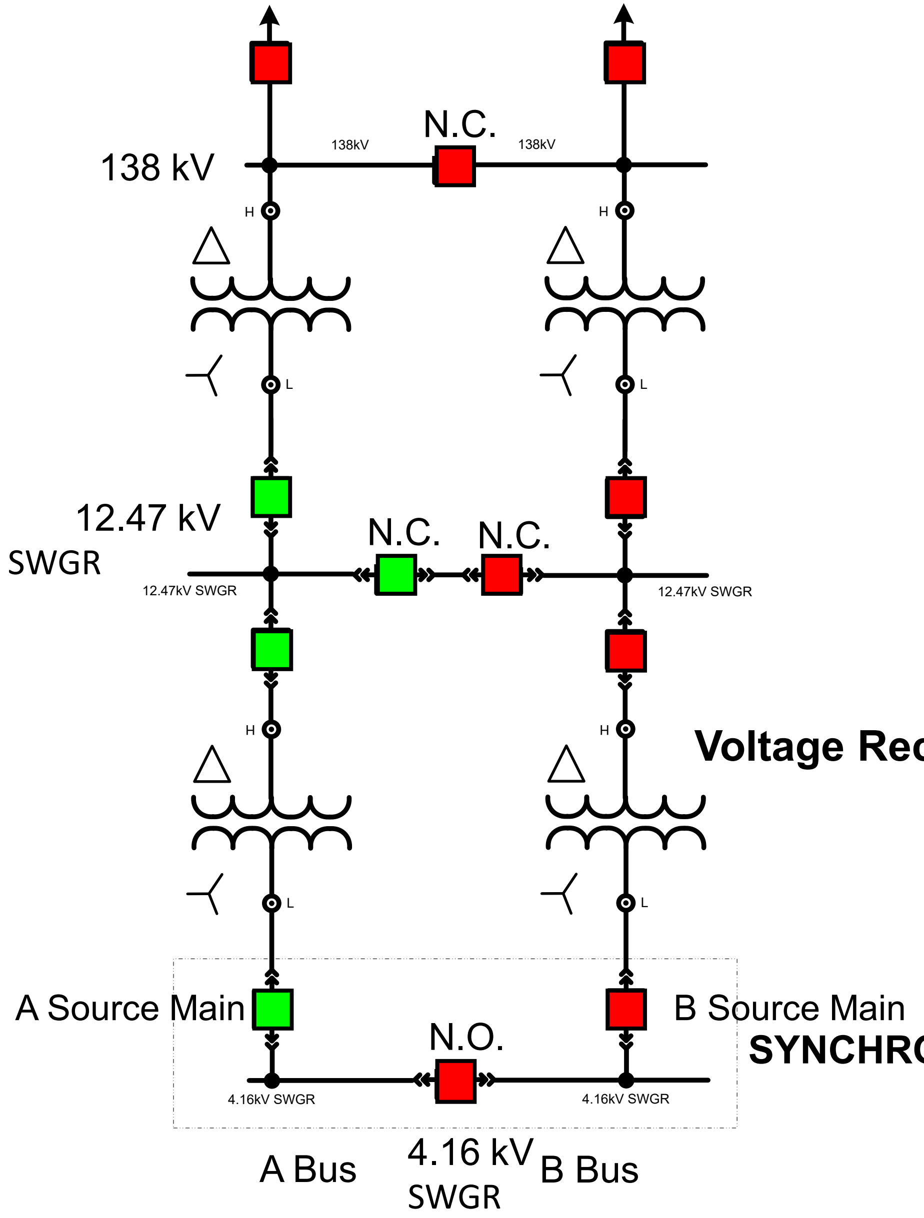
FAULT CLEARED

Voltage Recovering

MBT Initiate

Motors Spinning Down

Industrial Redundant Incoming Source

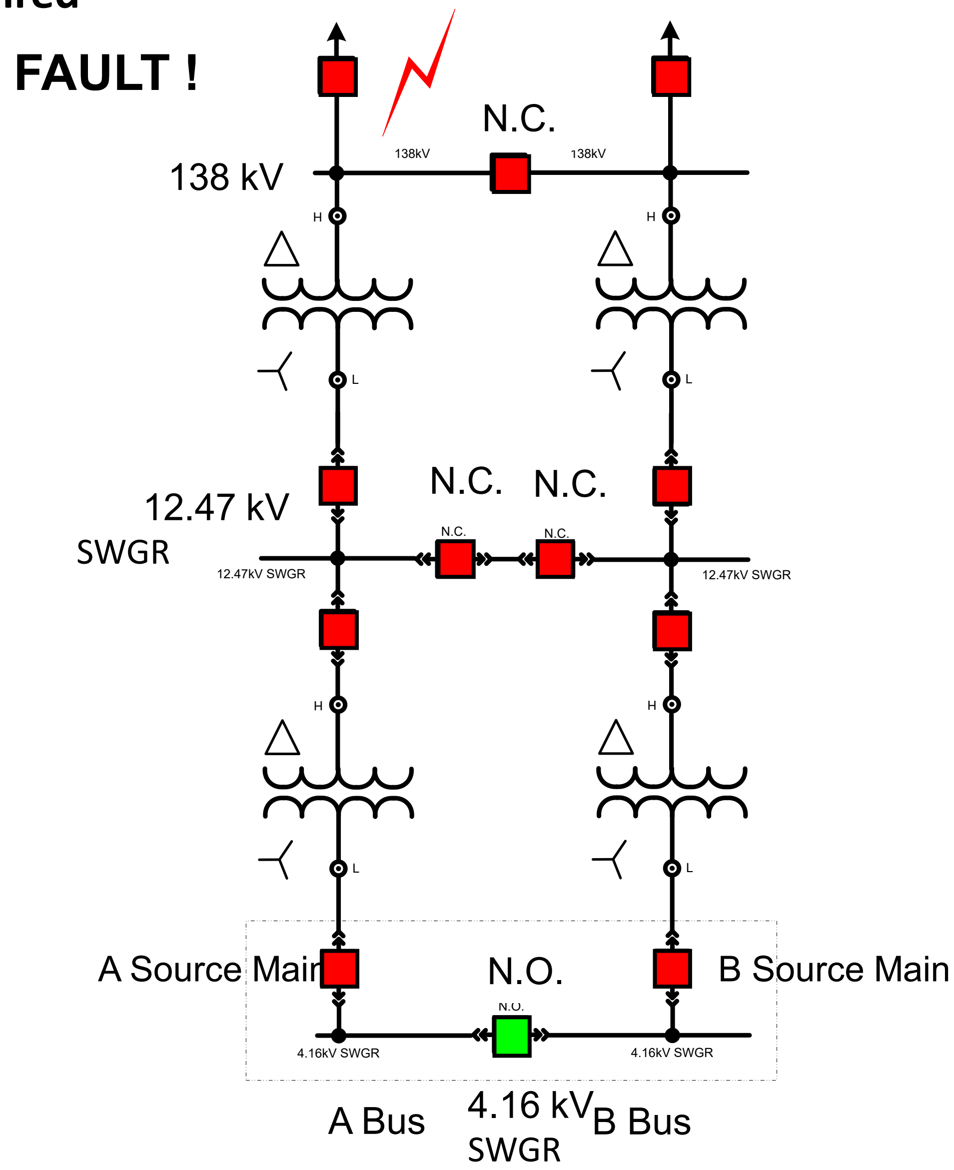


Voltage Recovers

SYNCHRONOUS TRANSFER COMPLETED

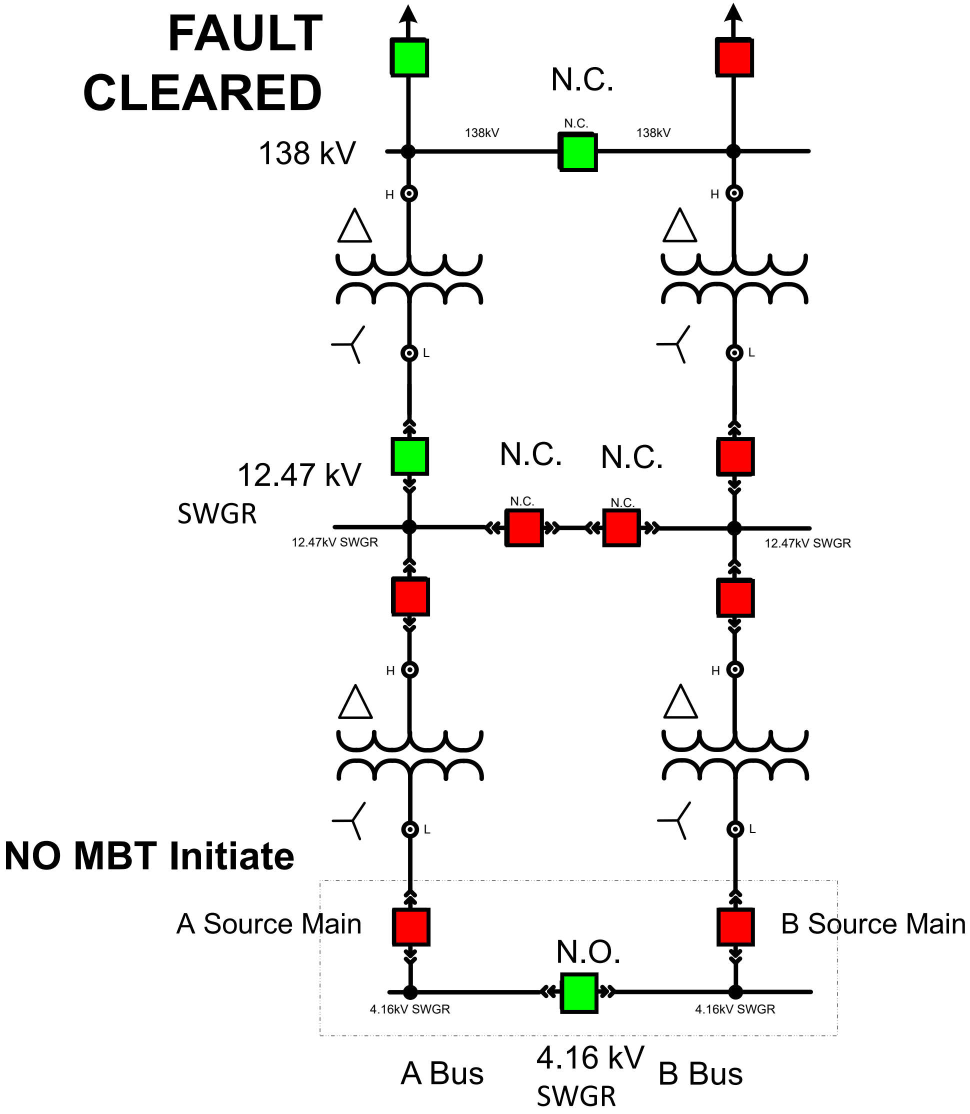
Industrial Redundant Incoming Source

No Motor Bus Transfer Initiate Required

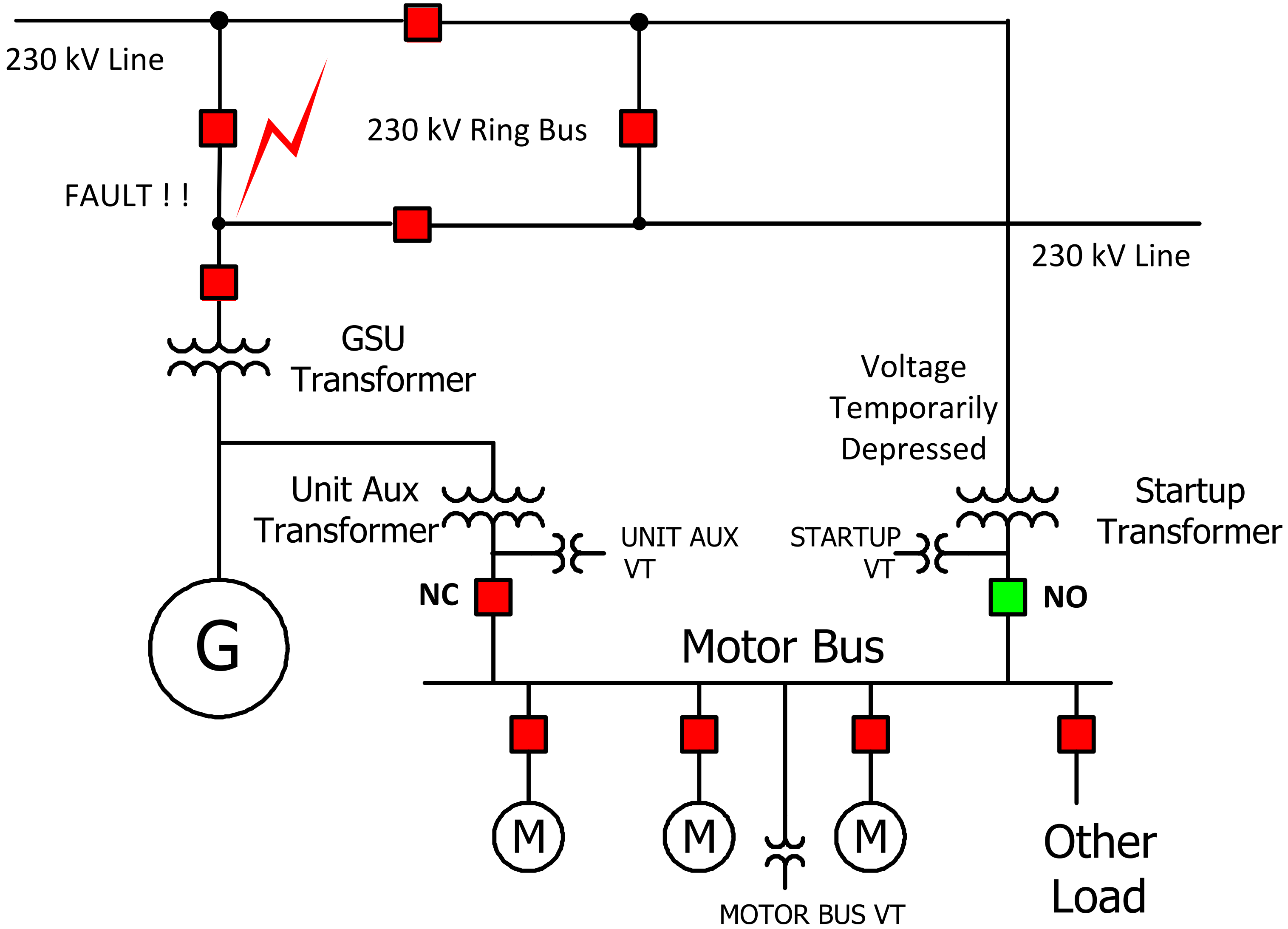


Industrial Redundant Incoming Source

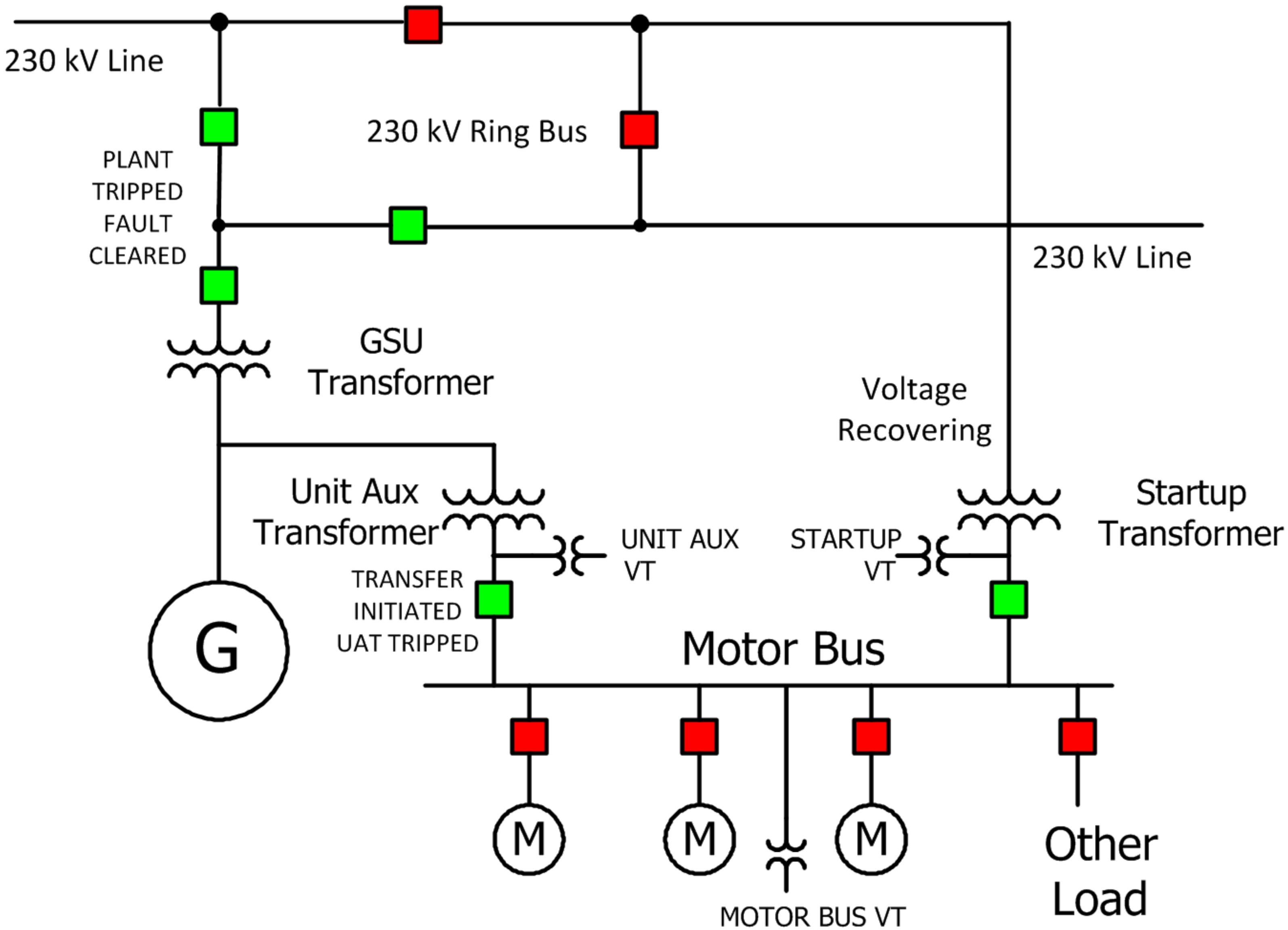
No Motor Bus Transfer Initiate Required



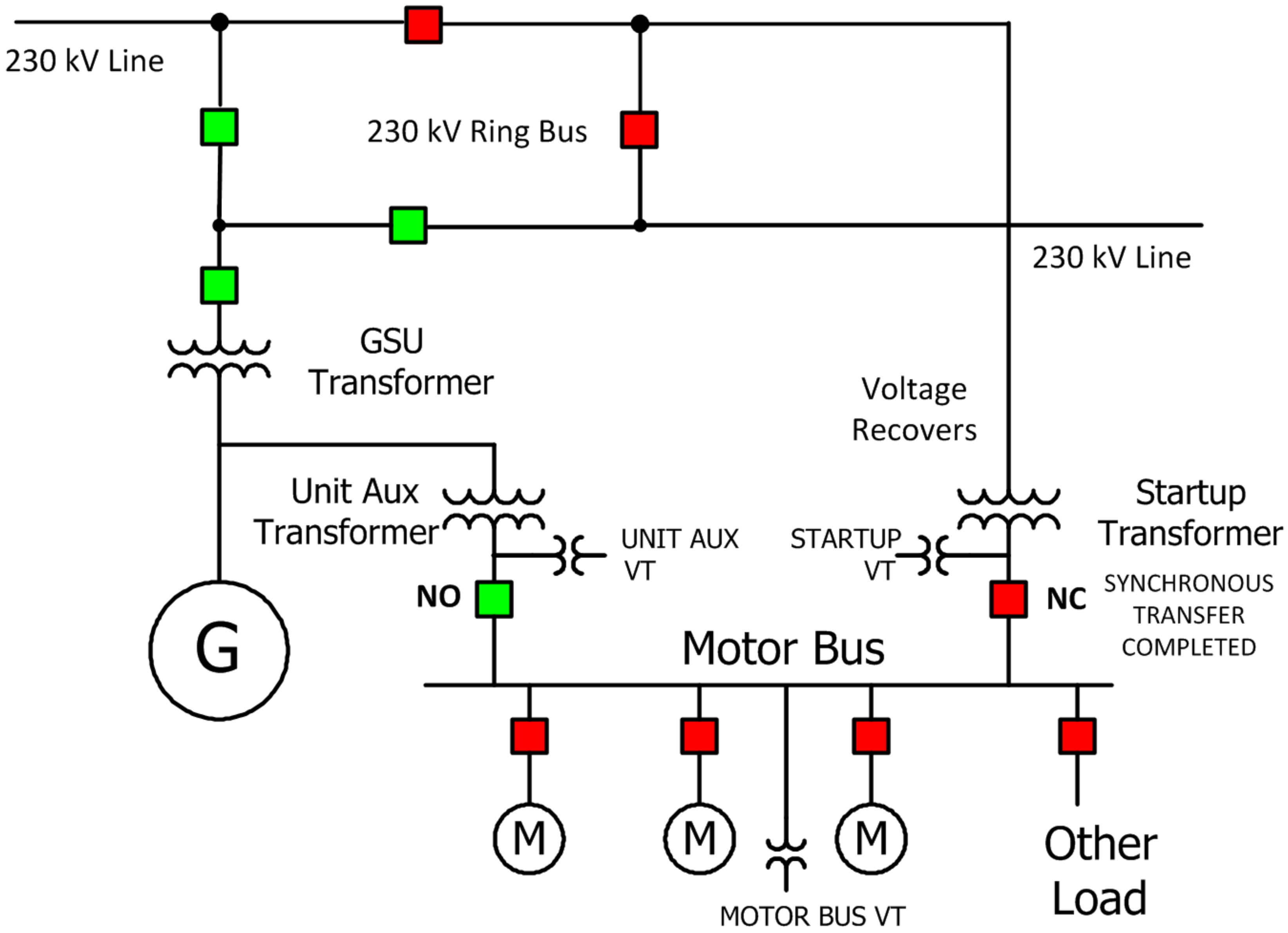
Fault at Generating Station Ring Bus - MBT Initiate Required



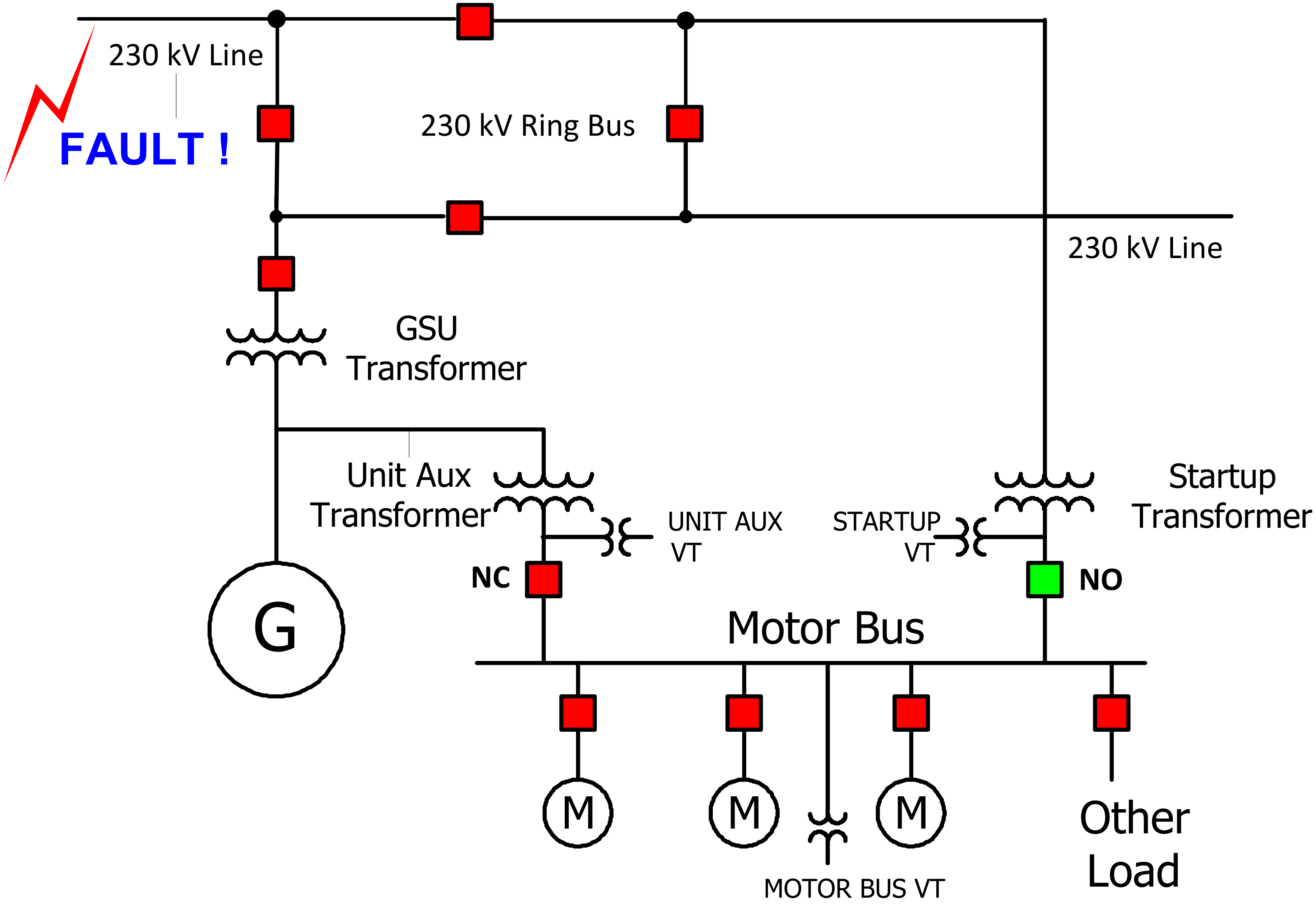
Fault at Generating Station Ring Bus



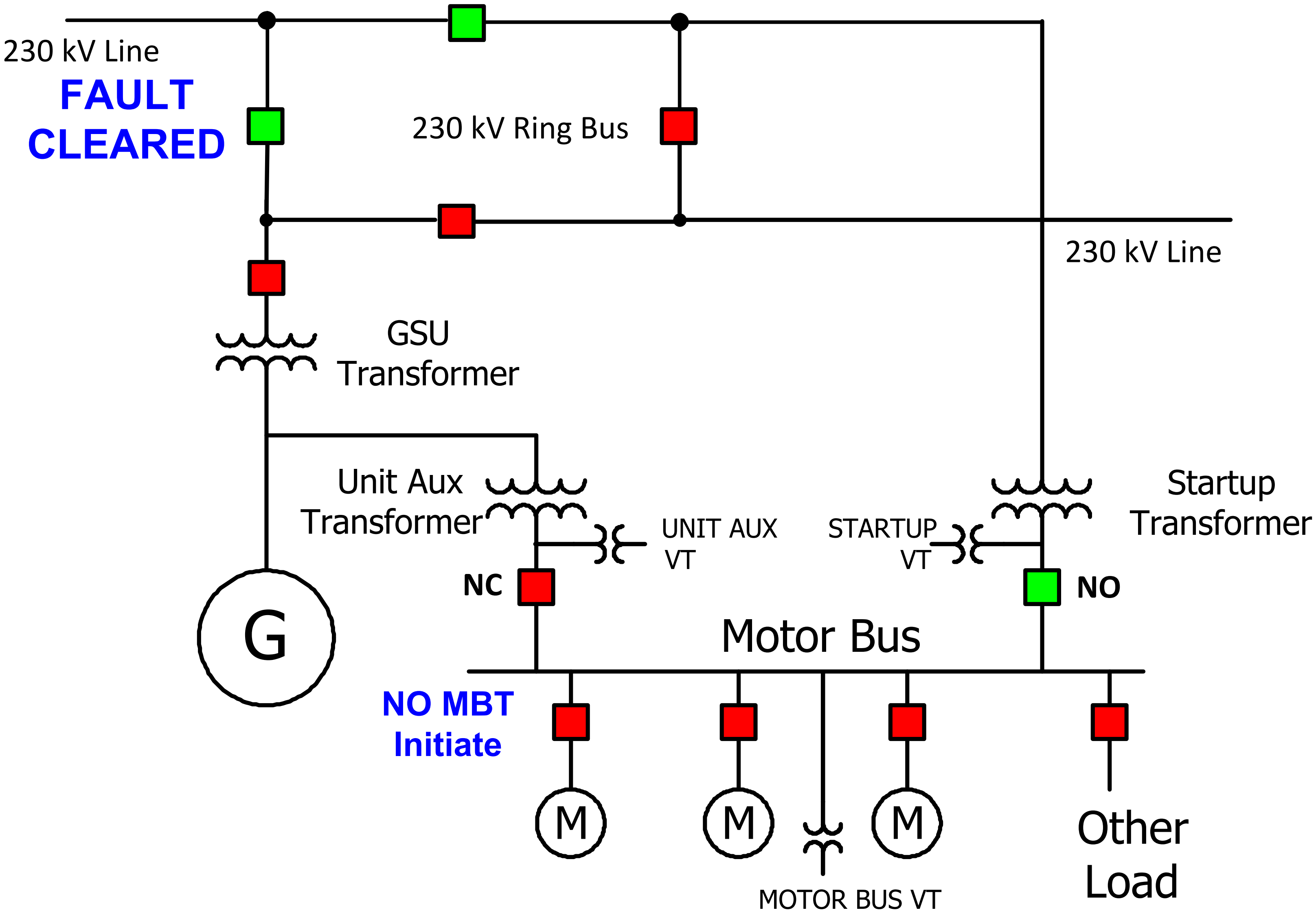
Fault at Generating Station Ring Bus



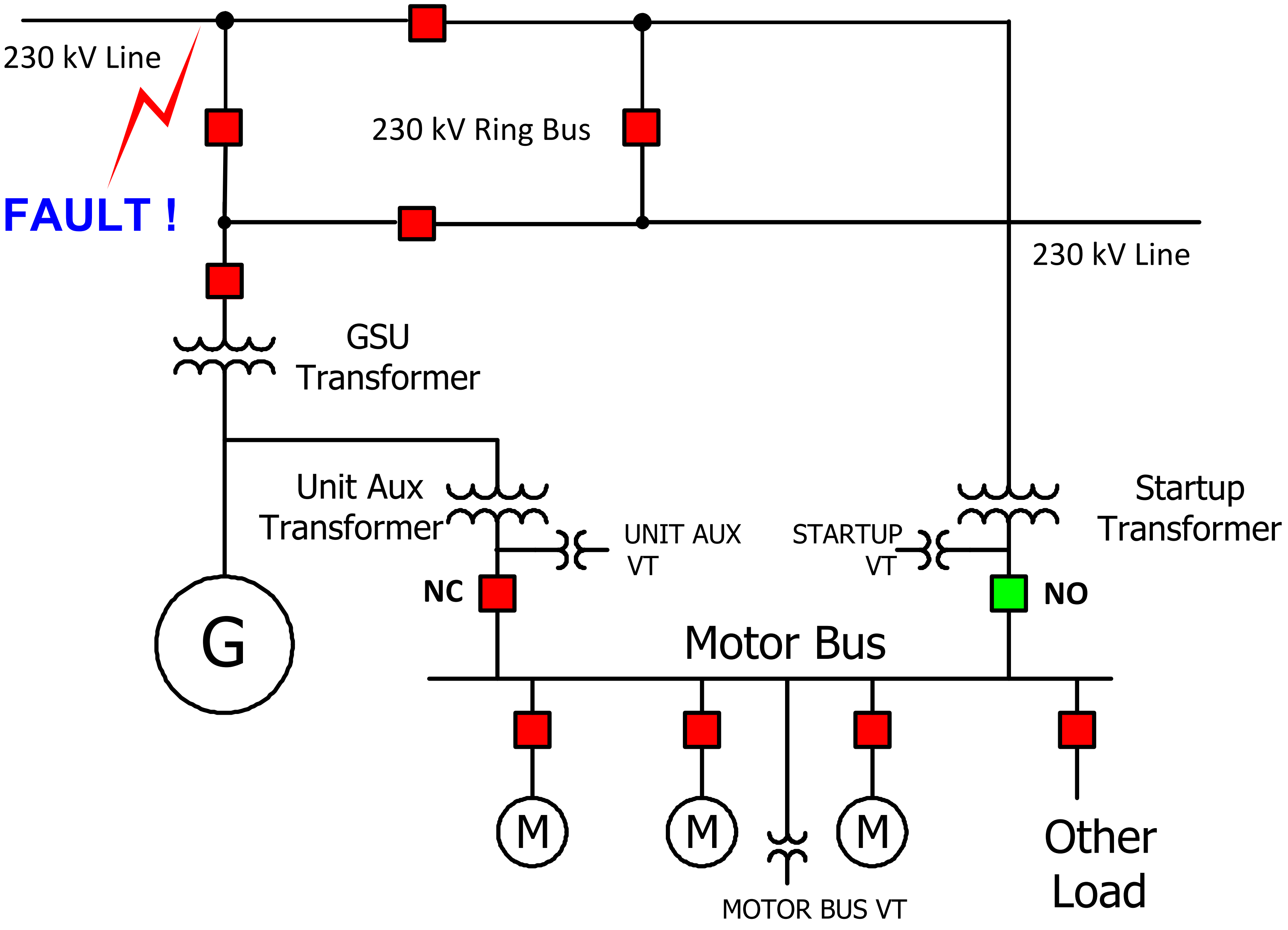
Distant Fault on 230 kV Line – NO MBT Initiate Required



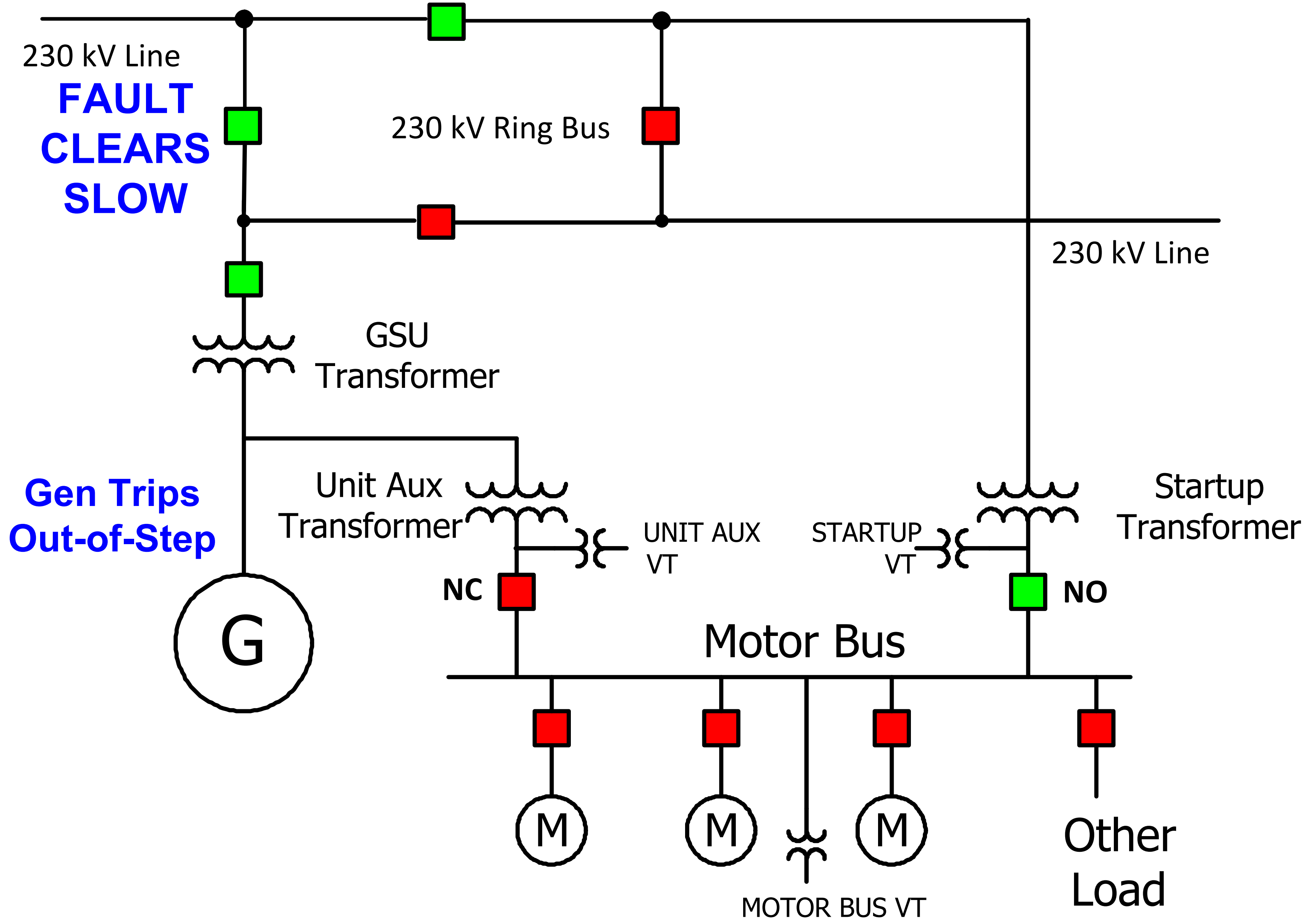
Distant Fault on 230 kV Line



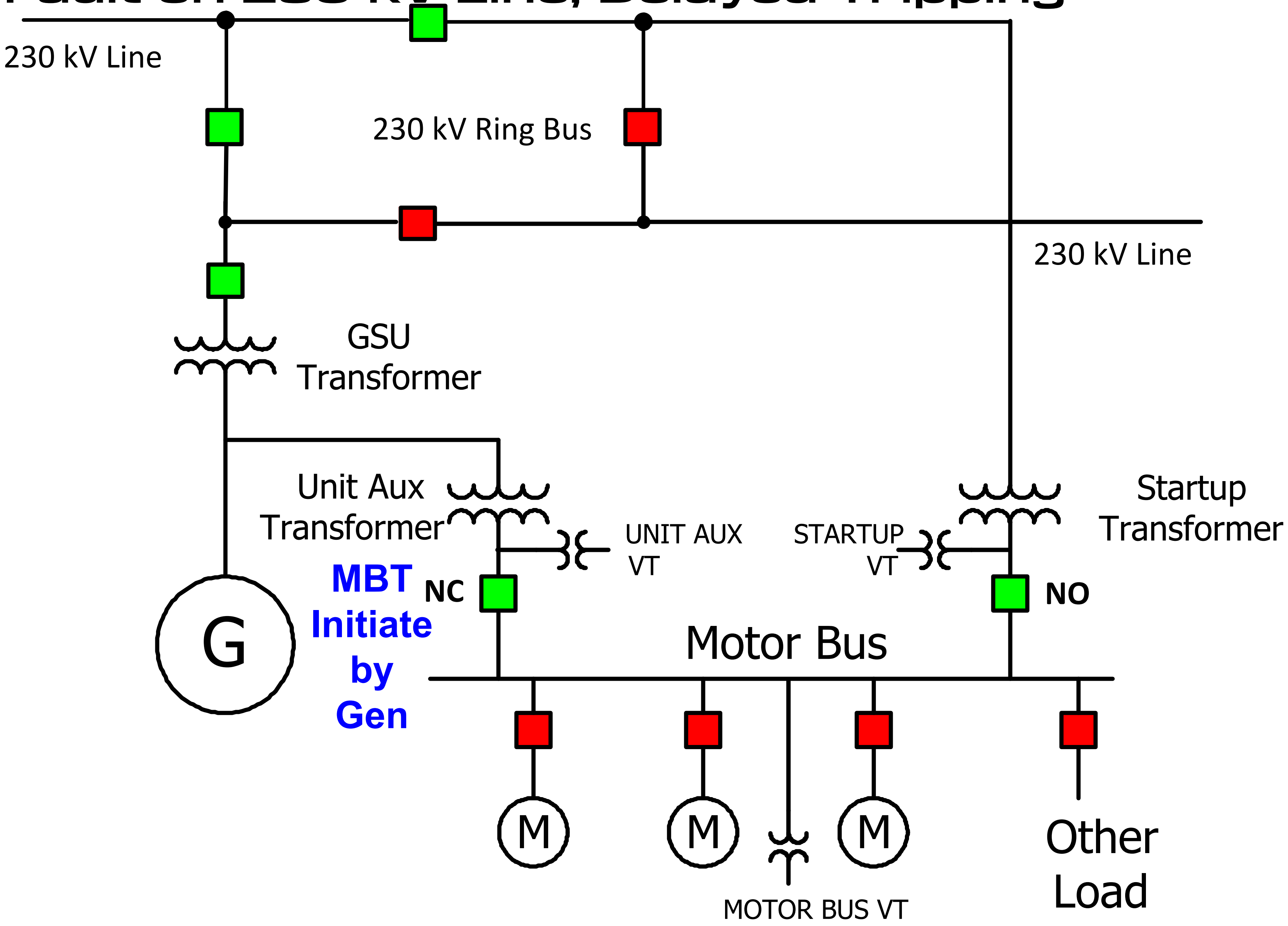
Close-in Fault on 230 kV Line



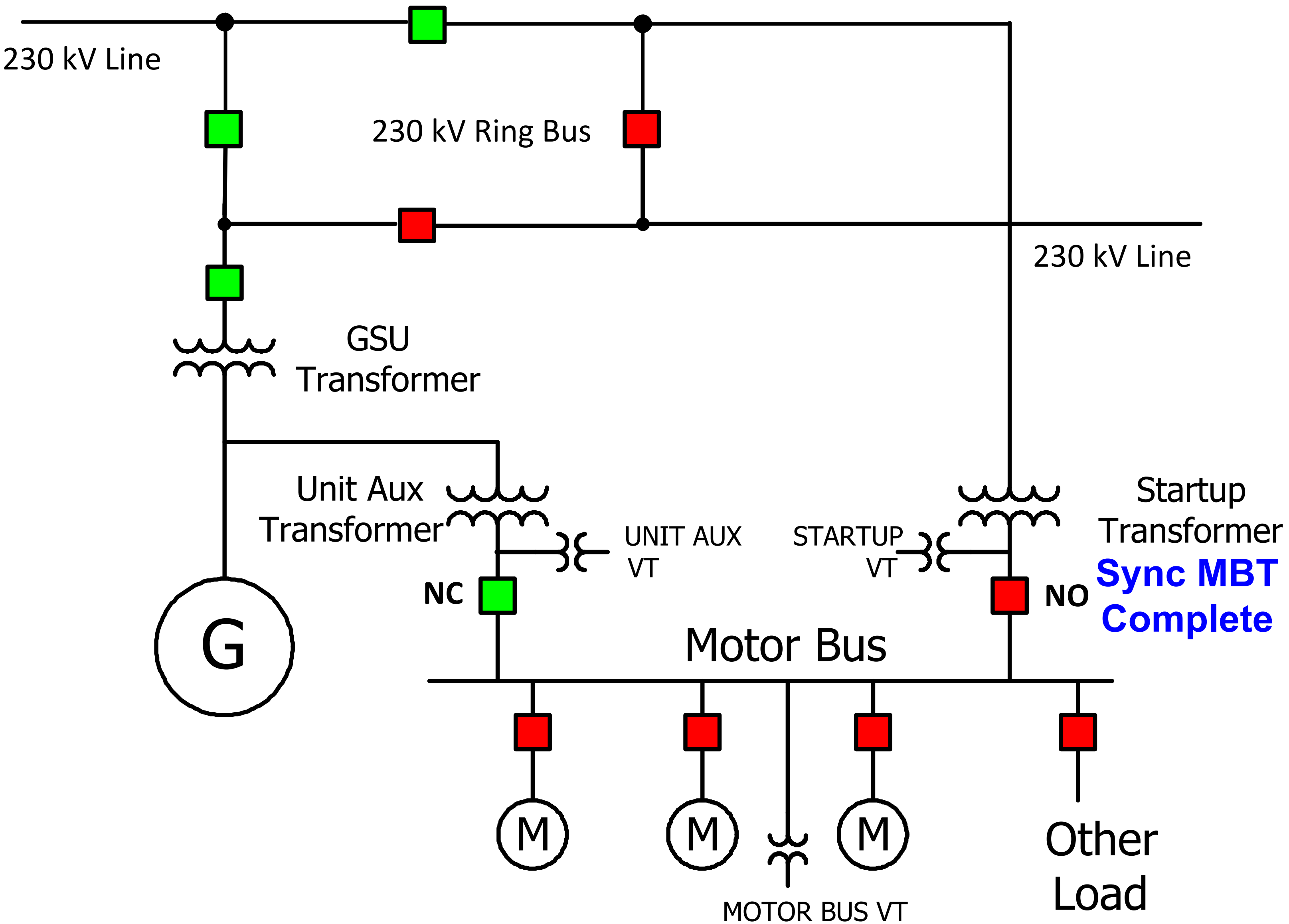
Close-in Fault on 230 kV Line, Delayed Tripping

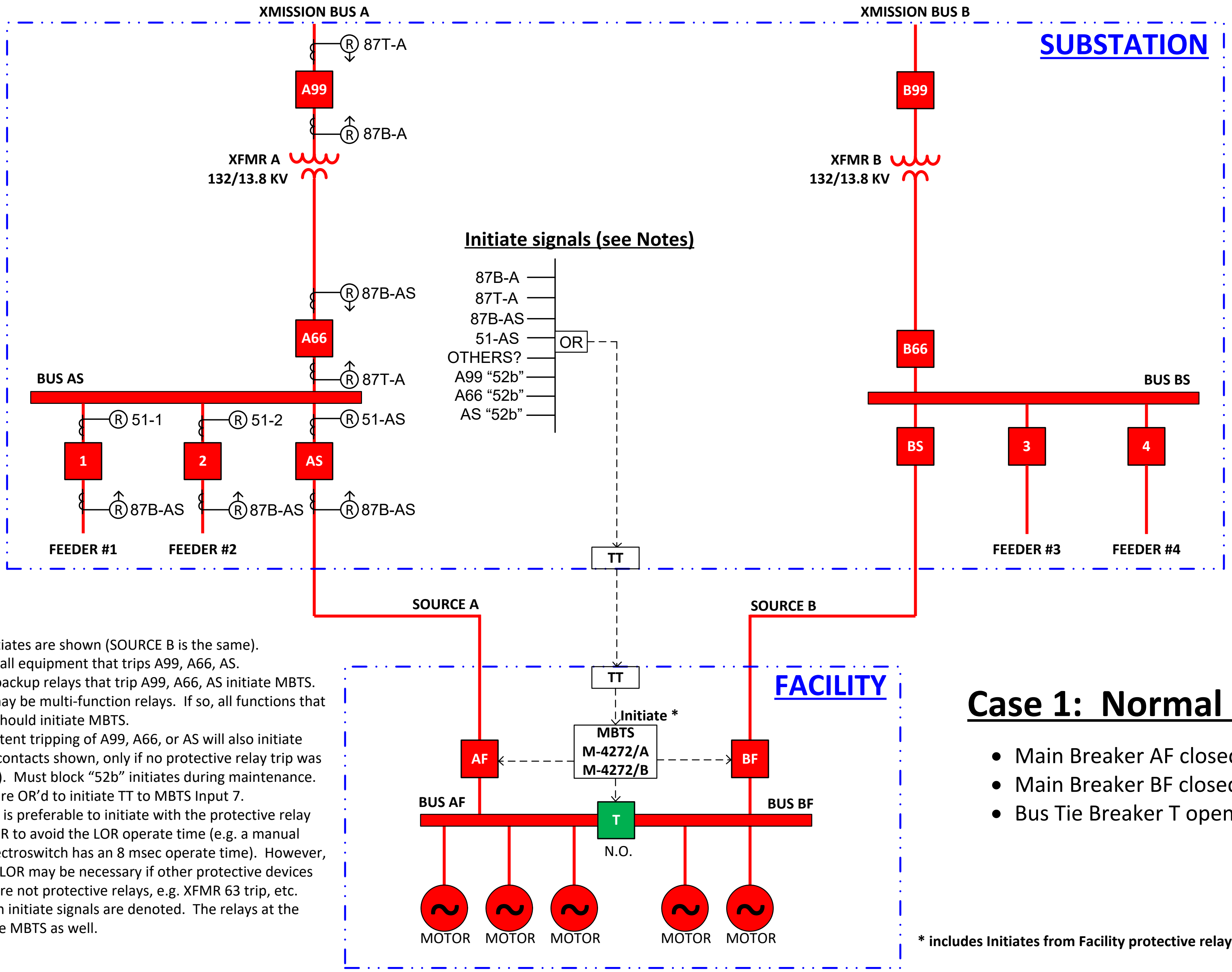


Close-in Fault on 230 kV Line, Delayed Tripping



Close-in Fault on 230 kV Line, Delayed Tripping





Notes:

1) Only SOURCE A initiates are shown (SOURCE B is the same).
2) Initiate MBTS with all equipment that trips A99, A66, AS.
3) Both primary and backup relays that trip A99, A66, AS initiate MBTS.
4) Protective relays may be multi-function relays. If so, all functions that trip A99, A66, AS should initiate MBTS.
5) Accidental/inadvertent tripping of A99, A66, or AS will also initiate MBTS with “52b” contacts shown, only if no protective relay trip was issued (see Case 8). Must block “52b” initiates during maintenance.
6) All initiate signals are OR’d to initiate TT to MBTS Input 7.
7) If 86 LOR is used, it is preferable to initiate with the protective relay rather than the LOR to avoid the LOR operate time (e.g. a manual reset LOR from Electroswitch has an 8 msec operate time). However, initiating with the LOR may be necessary if other protective devices trip the LOR that are not protective relays, e.g. XFMR 63 trip, etc.
8) Only the Substation initiate signals are denoted. The relays at the Facility may initiate MBTS as well.

Case 1: Normal Operation

- Main Breaker AF closed
- Main Breaker BF closed
- Bus Tie Breaker T open

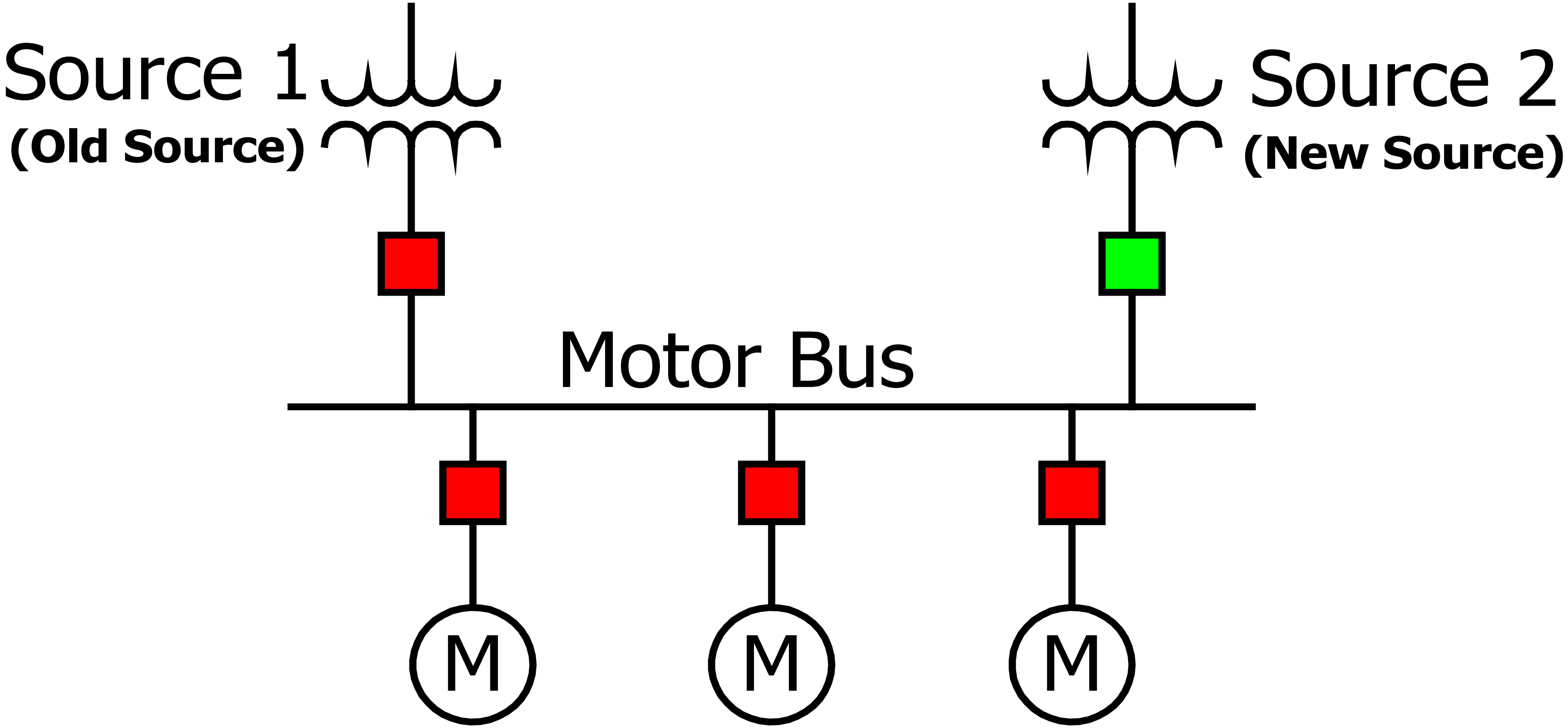
*** includes Initiates from Facility protective relays that trip AF and BF**

Lockouts

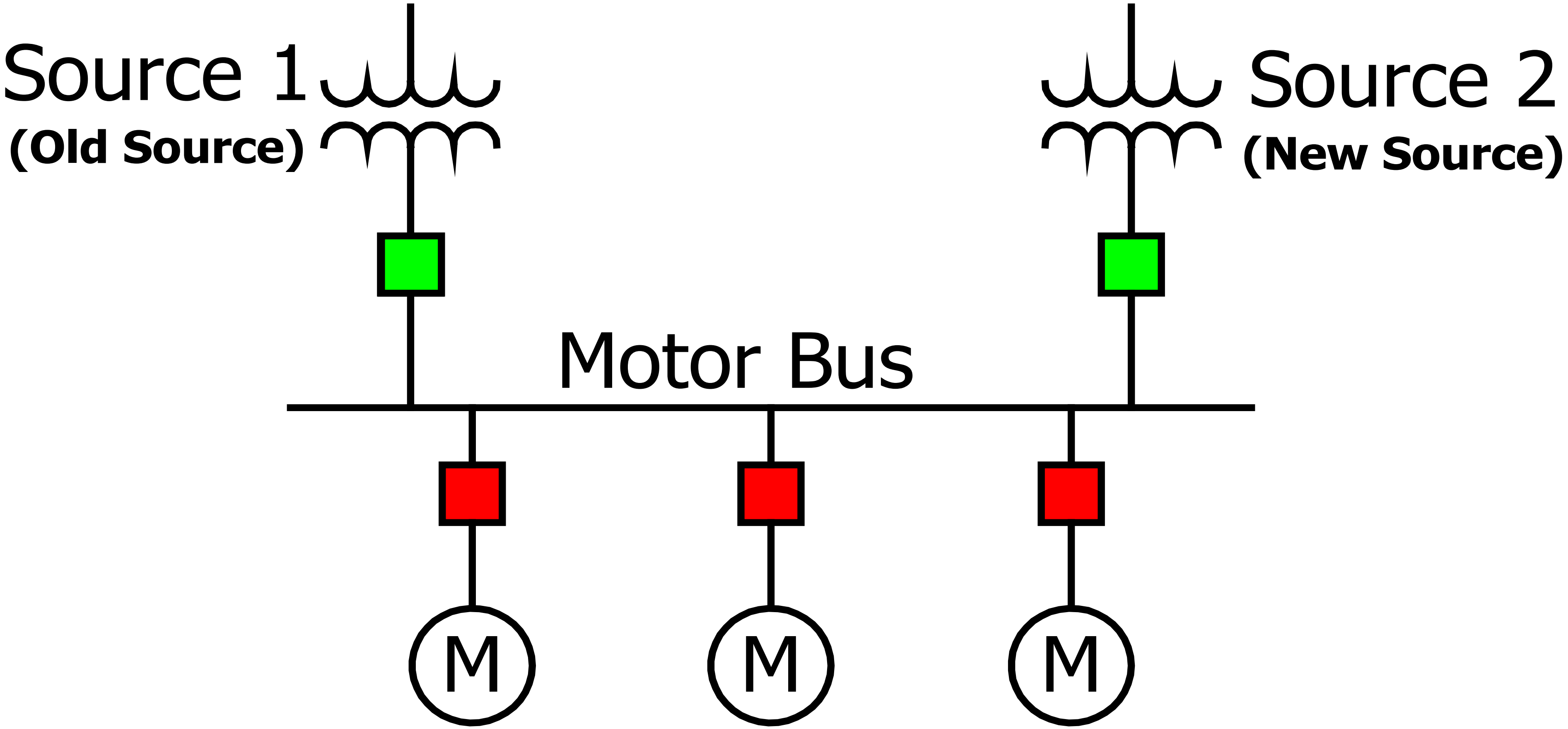
Both Breakers Open or Closed - Lockout

- If both breakers end up in the open state, due to an external operation that opens the old source breaker while leaving the new source breaker open, no transfer sequence shall be initiated. Furthermore, any subsequent initiation of a transfer sequence while the breakers are in this state shall be blocked. Alternatively, it may be selected to initiate an Auto Close, Open Transition Transfer.

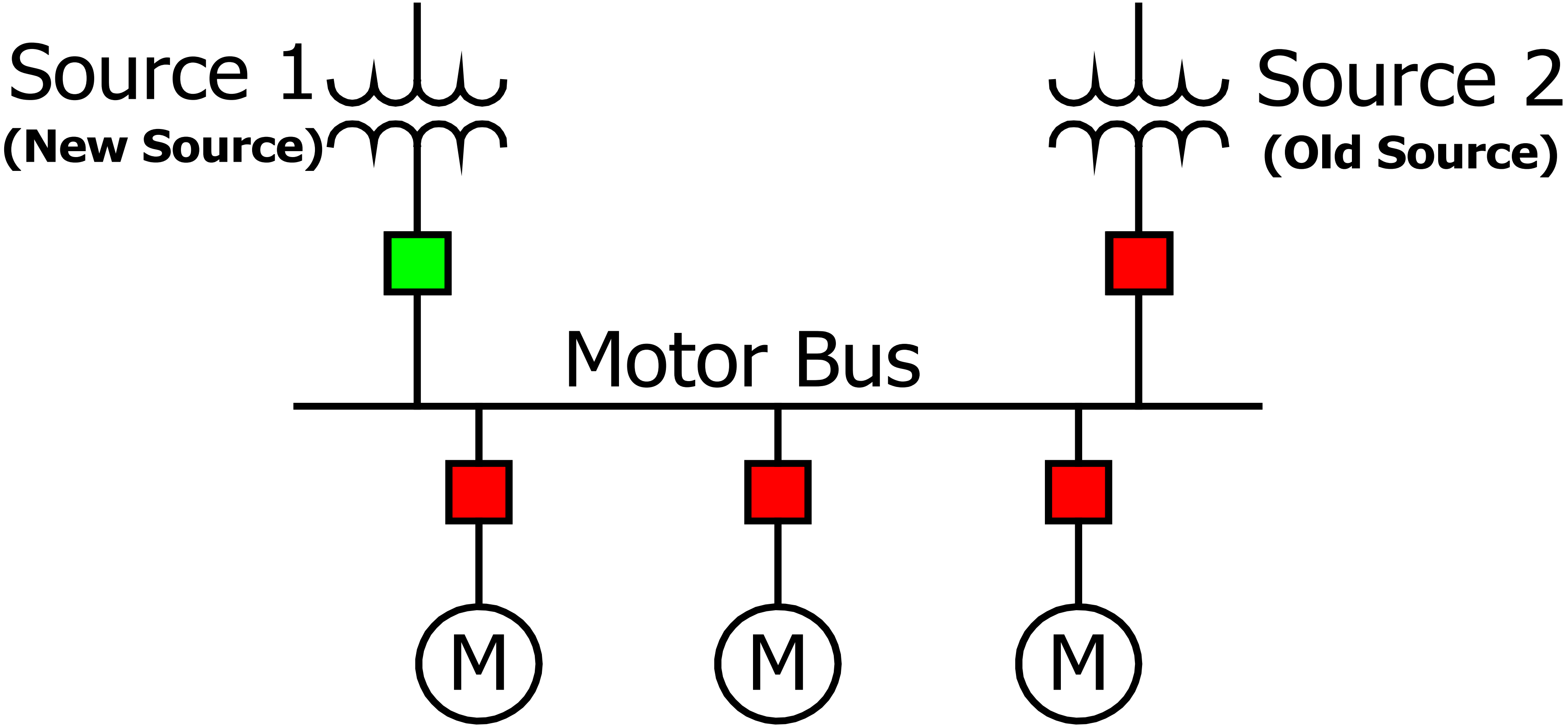
Both Breakers Open: Auto Close Initiate or Block Transfer



Both Breakers Open: Block Transfer



Both Breakers Open: Auto Close Initiate Open Transition Transfer



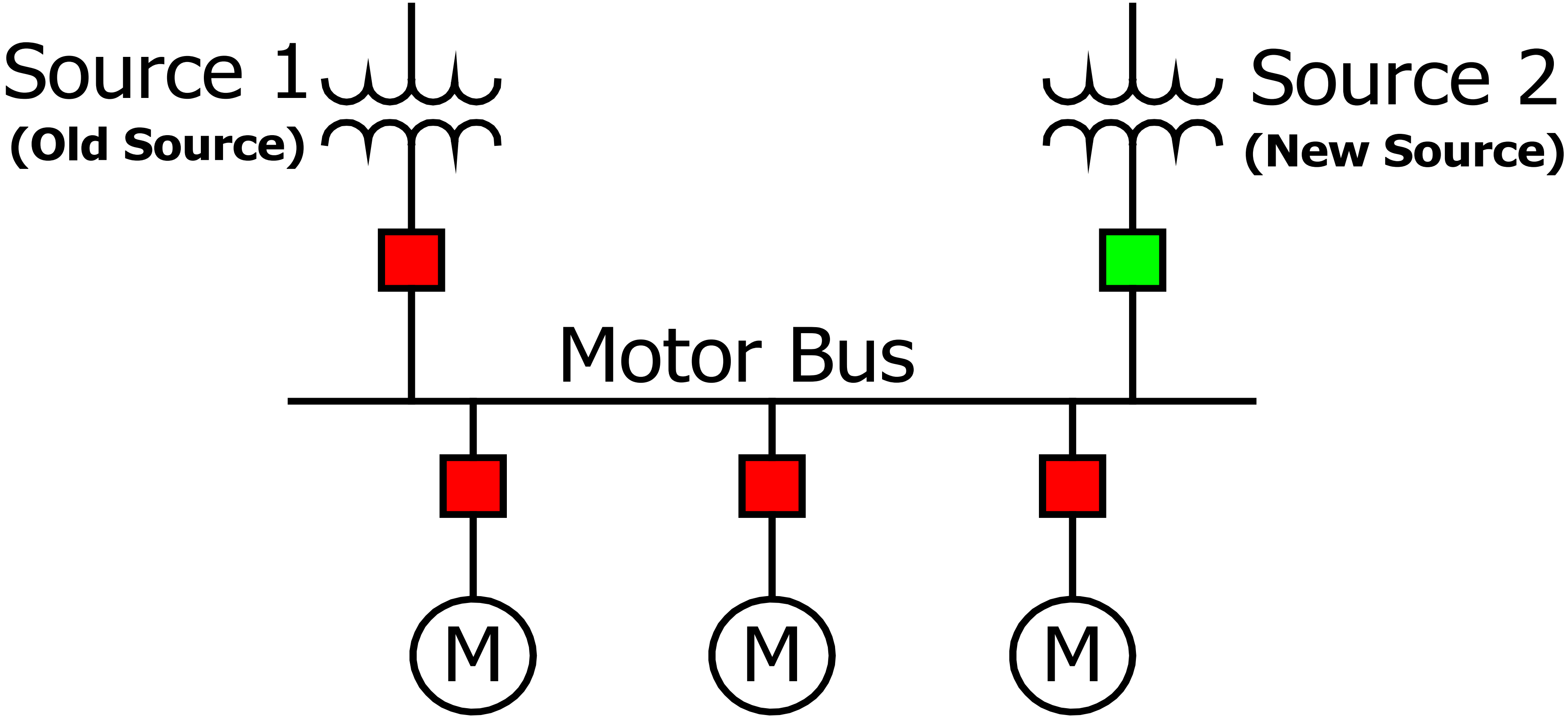
Lockouts

Both Breakers Open or Closed - Lockout

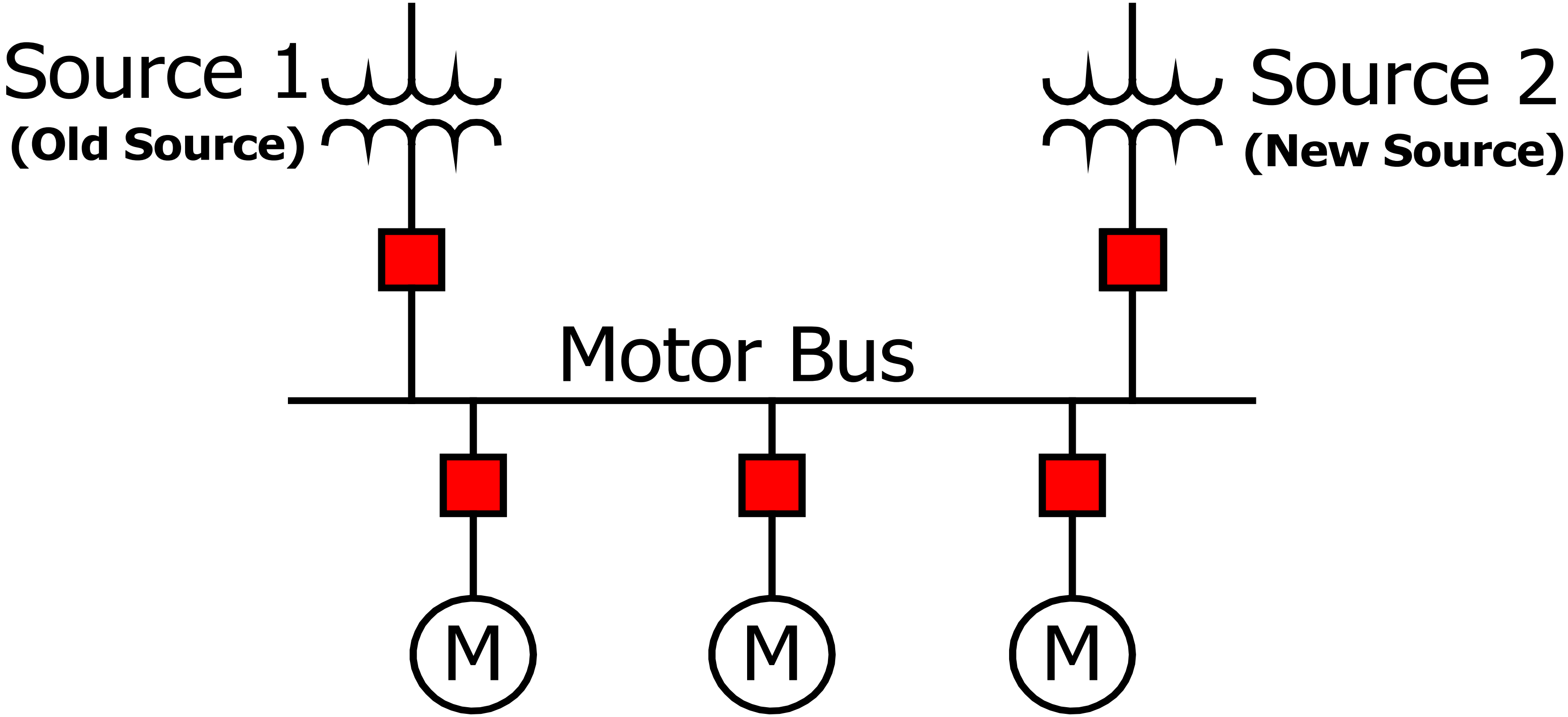
- If both breakers end up in the closed state, due to an external operation that closes the new source breaker while leaving the old source breaker closed, no transfer sequence shall be initiated. Furthermore, any subsequent initiation of a transfer sequence while the breakers are in this state shall be blocked. Alternatively, if Auto Trip is enabled, it may be selected to either Trip the Breaker Just Closed or Trip the Originally Closed Breaker.

Both Breakers Closed –

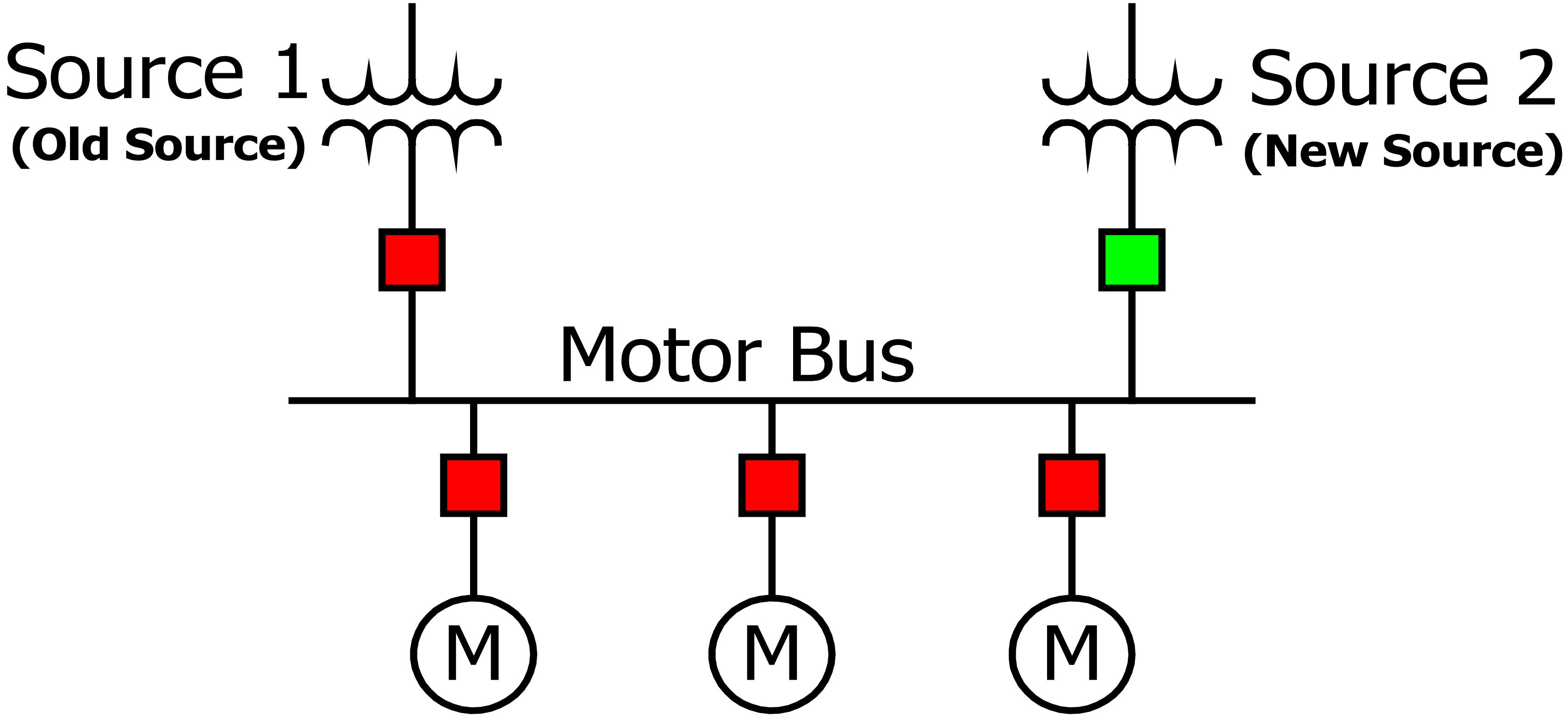
Inadvertent Parallelling: Auto Trip Initiate or Block Transfer



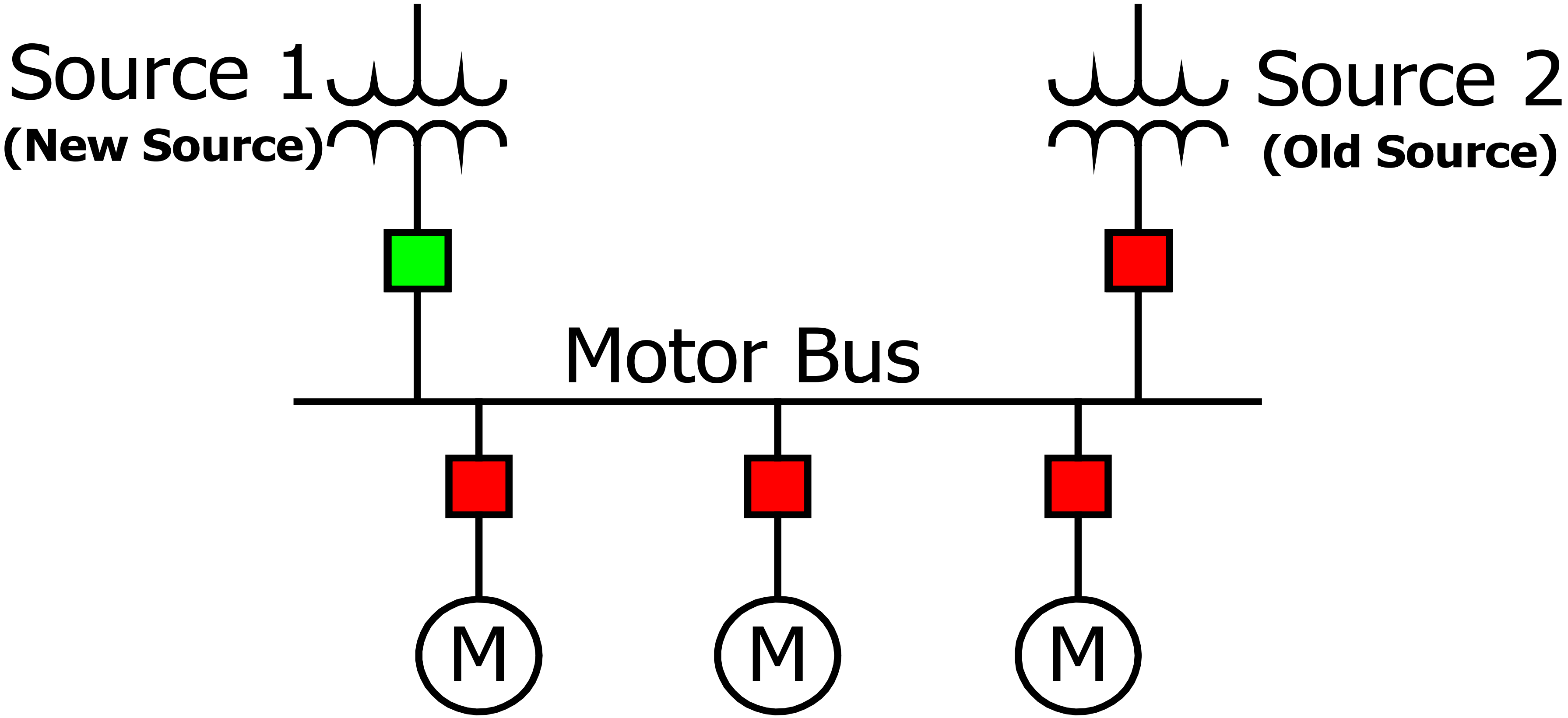
Both Breakers Closed: Block Transfer



Both Breakers Closed: Trip the Breaker Just Closed



Both Breakers Closed: Trip the Originally Closed Breaker



Lockouts

NOTE: The old source breaker SHALL NOT BE TRIPPED whenever any transfer initiate is blocked by any of the lockout conditions described below or if the new source voltage is outside the upper voltage limit and lower voltage limit .

Motor Bus Voltage Lockout

- Detects Motor Bus VT loss-of-potential (i.e. fuse loss) and may be programmed to block transfer, or if a transfer is required, can be programmed to proceed with a Fixed Time Transfer.

External Lockout

- External contact input blocks transfer.

Incomplete Transfer Lockout Time

- Timer starts at Transfer Initiate. If the transfer is not completed by timeout, then Transfer is Locked Out. Incomplete Transfer occurs if the old source breaker opens, but the new source breaker fails to close before timeout.

Transfer In Process Lockout

- Once a transfer is in process, all other transfer initiate inputs are ignored.

Lockout After Transfer

- Subsequent transfers are blocked for a set time after any transfer occurs.

Load Shed During Transfer

NOTE: For each of the following, Load Shed may be enabled or disabled.

Load Shed Coincident with Fast Transfer

- EXAMPLE: This may be used to disconnect motor loads from the aggregate bus, coincident with the command to trip the old source breaker, if the new source is not designed to pick up the full motor bus load.

Load Shed After Fast Transfer Window and Before In-Phase Attempt

- EXAMPLE: This may be used to disconnect large synchronous motors from the aggregate bus prior to In-Phase Transfer which may close in sync but at a high slip rate.

Load Shed Coincident with Residual Voltage Transfer

- EXAMPLE: This may be used to disconnect motor loads from the aggregate bus just prior to Residual Voltage Transfer so the remaining motors may reaccelerate.

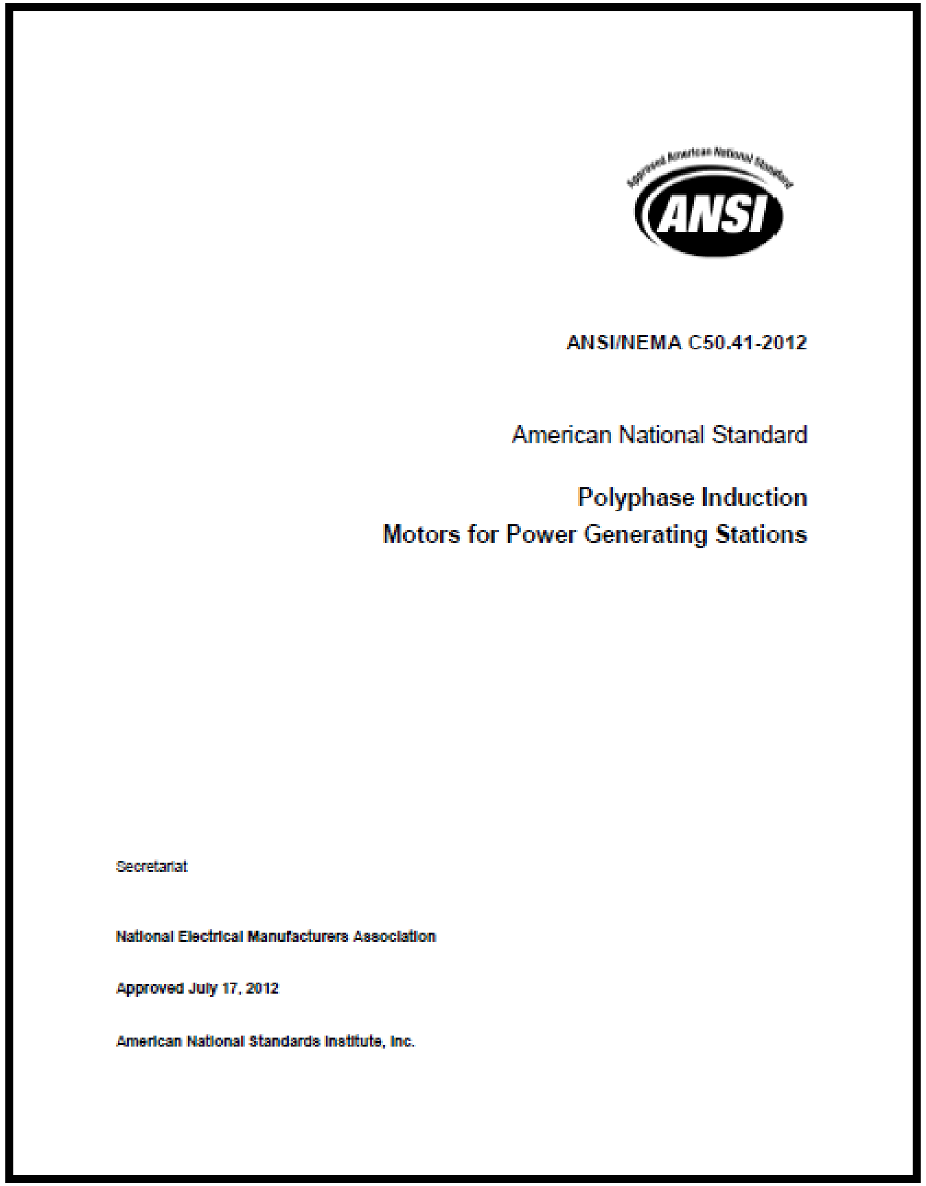
V/Hz Resultant from E_S and E_M ANSI/NEMA STANDARD C50.41-2012

C50.41 is an American National Standard Institute standard only found under NEMA

ANSI/NEMA C50.41-2012; Status is Current.

- C50.41 originally was a combined ANSI/IEEE standard, however it is no longer under the IEEE.
- The standard is now available on the NEMA website, and it is still active as an ANSI Standard.

ANSI/NEMA STANDARD C50.41-2012



ANSI/NEMA C50.41-2012

American National Standard

Polyphase Induction
Motors for Power Generating Stations

Secretariat

National Electrical Manufacturers Association

Approved July 17, 2012

American National Standards Institute, Inc.

Excerpts from ANSI/NEMA C50.41-2012

14 Bus Transfer or Reclosing

14.1 General

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 or momentary voltage interruptions and reclosing on the same bus. The magnitude of this transient current and torque may range from 2 to 20 times rated and is a function of the motor's electrical characteristics, operating conditions, switching time, rotating system inertia and torsional spring constants, number of motors on the bus, etc.

Any non-parallel bus transfer or reclosing subjects the motor (including the motor windings) and driven equipment to transient forces in excess of normal running values. Accordingly each bus transfer or reclosing reduces the life expectancy of the motor by some finite value, and it is recommended that, whenever possible, systems be designed to avoid (or minimize) bus transfer and reclosing.

The rotating masses of the motor-load system, connected by elastic shafts, constitute a torsionally responsive mechanical system that is excited by the motor electromagnetic (air-gap) transient torque that consist of the sum of an exponentially decaying, unidirectional component and an exponentially decaying oscillatory component at several frequencies, including power frequency and slip frequency. The resultant shaft torques may be either attenuated or amplified with reference to the motor electromagnetic (air-gap) torque.

Studies can be made of any particular system to determine the magnitude of the transient current and torque, and the electromagnetic interaction of the motor and the driven equipment. Although recommended, it is recognized that such studies are complex and require detailed knowledge of the motor, the driven equipment, and the power supply. In order to minimize this effect, the first torsional resonant frequency should not be within ±20 percent of rated electrical frequency.

For those applications where bus transfer or reclosing cannot be avoided, and where studies of the particular system have not been performed, the following may be employed as a guide and is based on limited studies and experience.

Excerpts from ANSI/NEMA C50.41-2012

14.2 Slow Transfer or Reclosing

A slow transfer or reclosing is defined as one in which the length of time between disconnect of the motor from the power supply and reclosing onto the same or another power supply is delayed until the motor rotor flux linkages have decayed sufficiently so that the transient current and torque associated with the bus transfer or reclosing will remain within acceptable levels.

To limit the possibility of damaging the motor or driven equipment, or both, it is recommended that the system be designed so that the resultant volts per hertz vector between the motor residual volts per hertz vector and the incoming source volts per hertz vector at the instant the transfer or reclosing is completed does not exceed 1.33 per unit volts per hertz on the motor rated voltage and frequency bases. This recommendation requires that power factor correction capacitors shall not be connected to the motor terminals during the transfer.

Slow transfer or reclosing can be accomplished by a time delay relay equal to or greater than 1.5 times the open-circuit alternating-current time constant of the motor (see NEMA MG1-1.60). If several motors are involved, the time delay should be based on the longest open-circuit time constant of any motor on the system being transferred or reclosed.[1]

[1] The 1.5 times the open-circuit alternating-current time constant criterion is more conservative than the 1.33 per unit volts per hertz criterion for high speed transfer. The 1.5 value accounts for these factors including the effects of switching an unsynchronized system on relay protection schemes.

Excerpts from ANSI/NEMA C50.41-2012

14.3 Fast Transfer or Reclosing

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 (δ) 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 exceed1.33 per unit volts per Hz on the motor rated voltage and frequency basis. See Figure 2.

For fast transfer or reclosing, calculations or tests should be performed by the user to determine the expected vectorial volts per hertz. Calculations or test conditions should account for any phase angle difference between the incoming and running power supplies. 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. If the user is concerned that the resultant volts per hertz during fast transfer or reclosing could be excessive based on testing, calculations, or other information, high-speed synchronizing check devices are available that can supervise this switching operation.

14.4 Recommendations

Power systems should be designed to limit bus transfer or reclosing to either slow transfer or reclosing as defined in 14.2 or fast reclosing as defined in 14.3, or both.

V/Hz Resultant from E_S and E_M

ANSI/NEMA STANDARD C50.41-2012

$$E_R = \sqrt{{E_S}^2 + {E_M}^2 - 2E_S E_M \cos\theta}$$

E, expressed as V/Hz, = per unit voltage ÷ per unit frequency

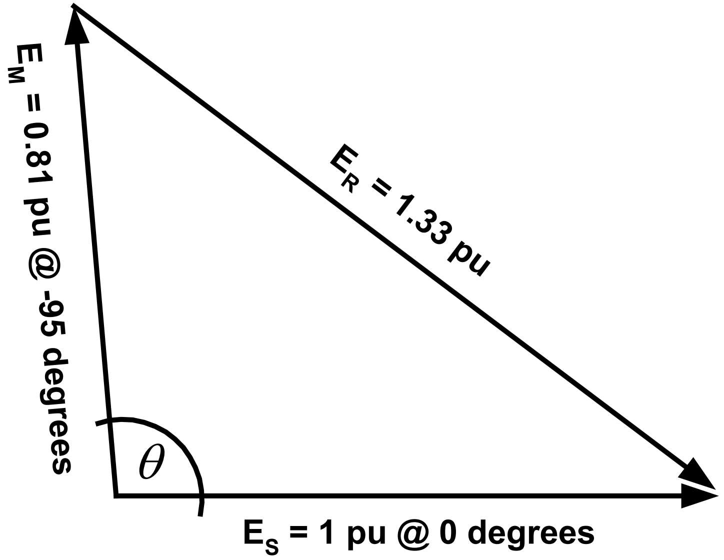
Where:

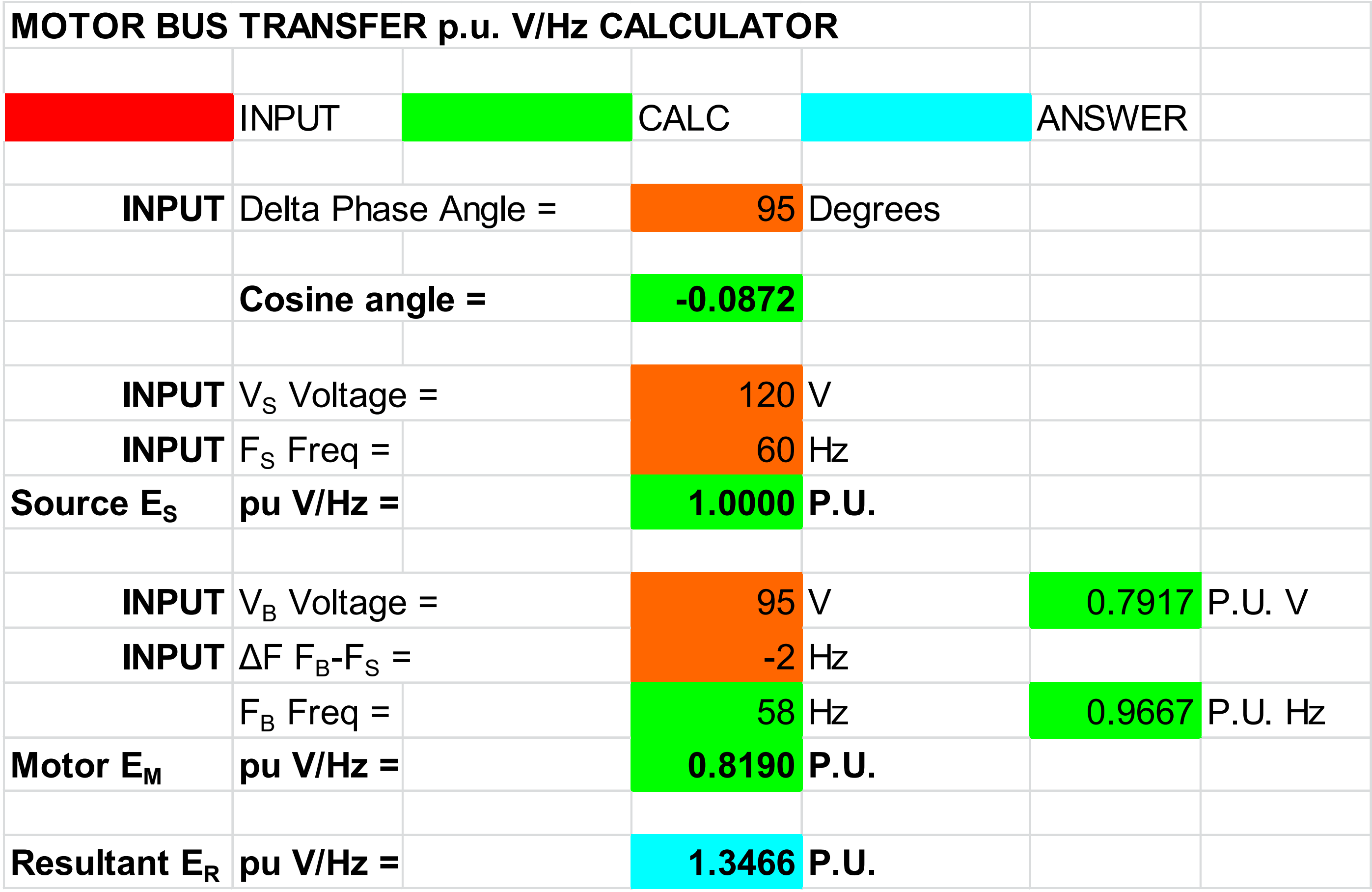
- E_R = resultant per unit V/Hz across the open breaker
- E_S = per unit V/Hz of the new source
- E_M = per unit V/Hz of the motor bus
- Cos θ = cosine of the phase angle between the new source and the motor bus

V/Hz Resultant from E_S and E_M

ANSI/NEMA STANDARD C50.41-2012

$$E_R = \sqrt{{E_S}^2 + {E_M}^2 - 2E_S E_M \cos\theta}$$





MOTOR BUS TRANSFER p.u. V/Hz CALCULATOR						
🟥	INPUT	🟩	CALC	🟦	ANSWER	
INPUT	Delta Phase Angle =		95	Degrees		
	Cosine angle =		**-0.0872**			
INPUT	V_S Voltage =		120	V		
INPUT	F_S Freq =		60	Hz		
Source E_S	**pu V/Hz =**		**1.0000**	**P.U.**		
INPUT	V_B Voltage =		95	V	0.7917	P.U. V
INPUT	ΔF F_B-F_S =		-2	Hz		
	F_B Freq =		58	Hz	0.9667	P.U. Hz
Motor E_M	**pu V/Hz =**		**0.8190**	**P.U.**		
Resultant E_R	**pu V/Hz =**		**1.3466**	**P.U.**		

It’s as Easy as A B C

- We first request the following drawings:
  - Single Line (One Line) diagram, showing the bus configuration, voltage levels of the buses and the breakers, protection functions that may be needed to initiate an automatic transfer or block a transfer, the actual motor types, motor rated voltage and frequency, and horse power ratings on each bus (or a separate motor list).
  - Three line diagram (AC Diagram) showing the PT and CT connections, ratios, and output ratings used for Motor Bus Transfer.
  - DC control schematics showing the trip and close circuits of each breaker to be used for Motor Bus Transfer, with breaker status contacts, trip and close times, and coil monitoring circuits if any.
- The Beckwith engineers with their extensive experience will then perform the analysis to determine how Motor Bus Transfer will work.
- BSE will then prepare a Technical and Commercial Quotation with our recommendations on how our MBTS will perform successful transfers.
- Initial Field Settings are determined during Technical Design Review.

Bus Transfer Acceptance Testing

- Verify scheme operation.
- Verify continuity of switching operation.
- Enable equipment in normal operating state.
- Initiate transfer and monitor for each transfer type:
  - Fast Transfer.
  - In-Phase Transfer.
  - Residual Voltage Transfer (not recommended).
- Verify acceptable operation.

Comments on Bus Transfer Spin Down Testing

- Is spin down allowed? Probably not.
- Offline spin down doesn’t simulate running conditions of plant and so is useless in determining settings.
- Settings are easily “tweaked” during commissioning.

Motor Bus Transfer Setting Considerations

- Fast Transfer:
  - Phase Angle Limit typically set at 20° to block closure at large phase angles.
  - Must consider the effect of the new source breaker closing time.
- In-Phase Transfer:
  - New source breaker closing time .
  - The Advance Angle to compensate for the Breaker Closing Time is automatically calculated.
  - ΔF Limit is typically set at the maximum of 15 Hz except for extraordinary circumstances.

Spin Down Analysis

CASE STUDY

Central Termoeléctrica Carbon II

Mexico

Motor Bus Transfer Application

Project Background

- Test Spindown data from pre-commissioning tests at the Carbon II station in Mexico with plant offline.
- Unit 1 is a 346.7 MVA generator with a three winding auxiliary transfer feeding two separate 7.2KV buses.
- The startup transformer is also a three winding transformer feeding two separate 7.2KV buses
- There are a total of four generators with the same configuration at this site.
- The breaker close time is 5.40 cycles.
- Real Spindown data captured with plant online after a successful Simultaneous Fast Transfer followed by a New Source false trip.

Motor Bus Transfer Application

Project Background

Motor Load Panel 2F1

Equipment	Capacity	Current	Speed
Feedwater Pump	4850 kW	495 A	1785 rpm
Condensate Pump	111.9 KW	114 A	1180 rpm
Controlled Circulation Pump	370 kW	695 A	1180 rpm
Water Circulation Pump	1231 kW	140 A	440 rpm
Auxiliaries Cooling Pump	336 kW	39.5 A	1185 rpm
Cooling Tower Service Transformer	2000 kVA		
Service Transformer	1500 kVA		
Ash Transport Blower	220 kW	22 A	1790 rpm
Forced Draft Fan	1350 kW	140 A	1180 rpm
Primary Air Fan	845 kVA	94 A	1193 rpm
Induced Draft Fan	1860 kW	195 A	710 rpm
Pulverizer	510 kW	67 A	590 rpm
Pulverizer	510 kW	67 A	590 rpm
Transformer- Precipitator & Ash Handler	1500 kVA		
High Pressure Pump	450 kW	44 A	1800 rpm

Real Spin Down Analysis

Determine Viability of Sequential Transfer with Fast Method of Transfer

- Find the point in time when the old source “b” breaker status contact closes, confirming that the old source breaker has opened, and then determine when a Sequential Transfer would occur by the Fast Transfer Method.
- The Volts per Hertz is calculated at the time the new source breaker would close.
  - To do the per unit V/Hz calculation you need the voltage of the motor bus and the new source, the delta frequency between the motor bus and the new source, and the phase angle between the motor bus and the new source.
- Determine the point in time when the old source “b” breaker status closes which is the point in time when the close command is sent to the new source breaker.
  - The initial phase angle at that point is 4.3°.
  - Determine the point 5.4 cycles to the right which is the closing time of the breaker to locate the point in time when the new source breaker contacts would close.

Spin Down Analysis

Sequential Transfer Mode; Fast Transfer Method

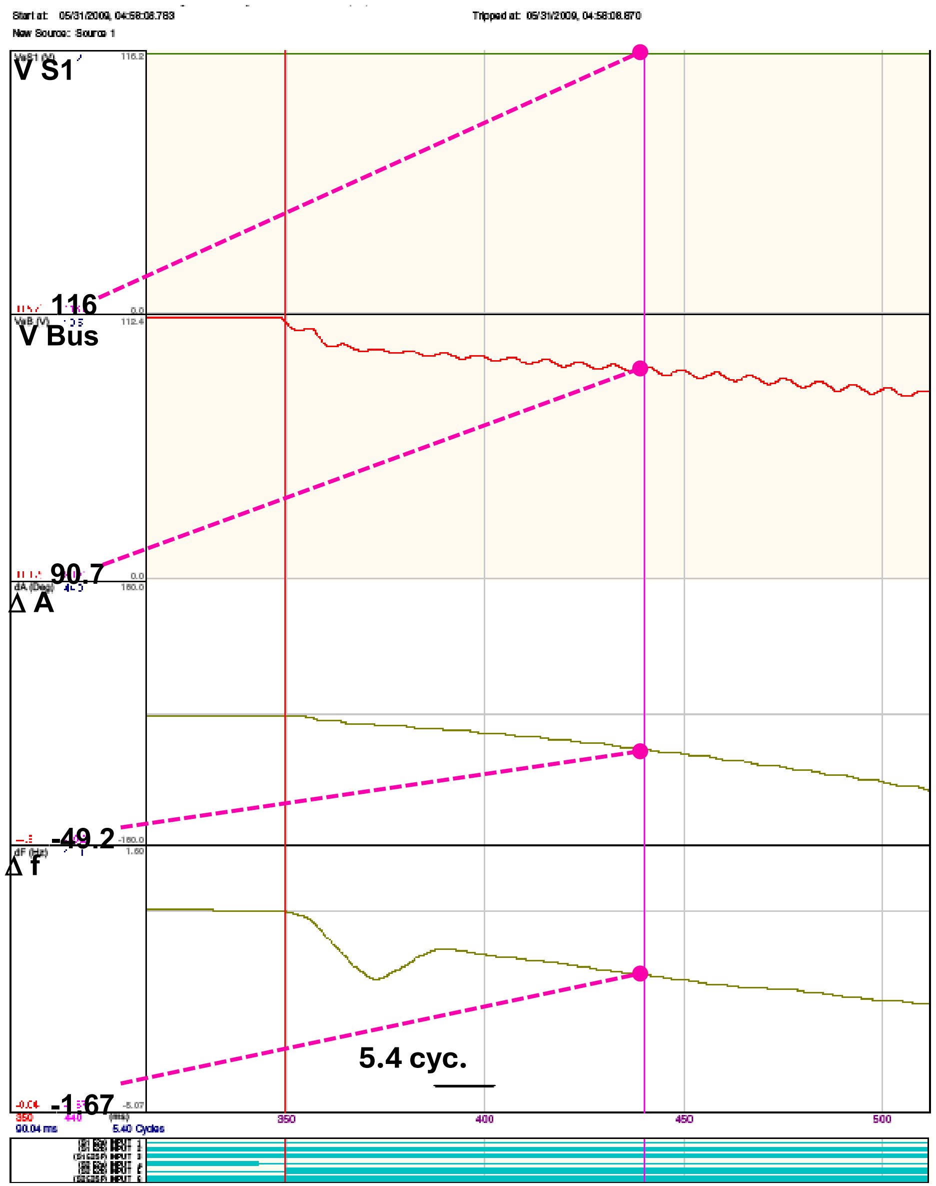
New Source Breaker Close

Source 1 = 116.0 Volts

Motor Bus = 90.7 Volts

Phase Angle = -49.2°

Delta Frequency = -1.67 Hz



Real Spin Down Analysis

- The maximum permitted V/Hz across the breaker that is closing is defined in ANSI/NEMA Standard C50.41-2012 Polyphase Induction Motors for Power Generating Stations, Paragraph 14, as 1.33V/Hz.
- The equation for the pre-closure Volts per Hertz is as follows:

$$E_R = \sqrt{E_S{}^2 + E_M{}^2 - 2E_S E_M \cos\theta}$$

E, expressed as V/Hz, = per unit voltage ÷ per unit frequency

Where:

- ER = resultant per unit V/Hz across the open breaker
- ES = per unit V/Hz of the new source
- EM = per unit V/Hz of the motor bus
- Cos θ = cosine of the phase angle between the new source and the motor bus

Real Spin Down Analysis

Sequential Transfer Mode; Fast Transfer Method

- Phase angle = 49.2 degrees
- Motor bus pu voltage = 90.7/116.0 = 0.7819pu Vrms
- Motor bus pu frequency = (60-1.67)/60 = 0.9722pu Hz
- E_M = 0.7819/0.9722 = 0.8043pu V/Hz
- **E_R = 0.7719pu V/Hz**

This is well within the 1.33 maximum per unit V/Hz defined by ANSI/NEMA C50.41

- Note that **during the 5.4 cycles (**90 ms) while the breaker is closing:
  - The motor bus voltage has dropped **19.5 V.**
  - Delta Frequency between the motor bus and the new source has increased by **1.63 Hz.**
  - Phase Angle difference has increased by **44.9 degrees.**

Real Spin Down Analysis

Analysis of Oscillography to Determine Settings; Sequential Fast Transfer Setting Calculations

- To determine an appropriate Fast Transfer Phase Angle Limit Setting, one must consider the disconnect phase shift of induction motors and, if the transfer is initiated by a system disturbance or fault, there can be a resultant rapid phase shift between the motor bus and the new source.
- Such a phase shift would have to be added to the initial angle of 4.3 degrees. Many consider 20 degrees a reasonable Phase Angle Limit for blocking a fast transfer.
- To perform an analysis to determine the effect of a close command sent just within this 20-degree limit, determine a point in time where the breaker close command would be sent just under 20 degrees.
- Find the point 5.4 cycles to the right which is the closing time of the breaker to locate the point in time when the new source breaker contacts would close. This is the worst case Sequential Fast Transfer.

Spin Down Analysis

Sequential Transfer Mode Fast Transfer Method Worst Case

New Source Breaker

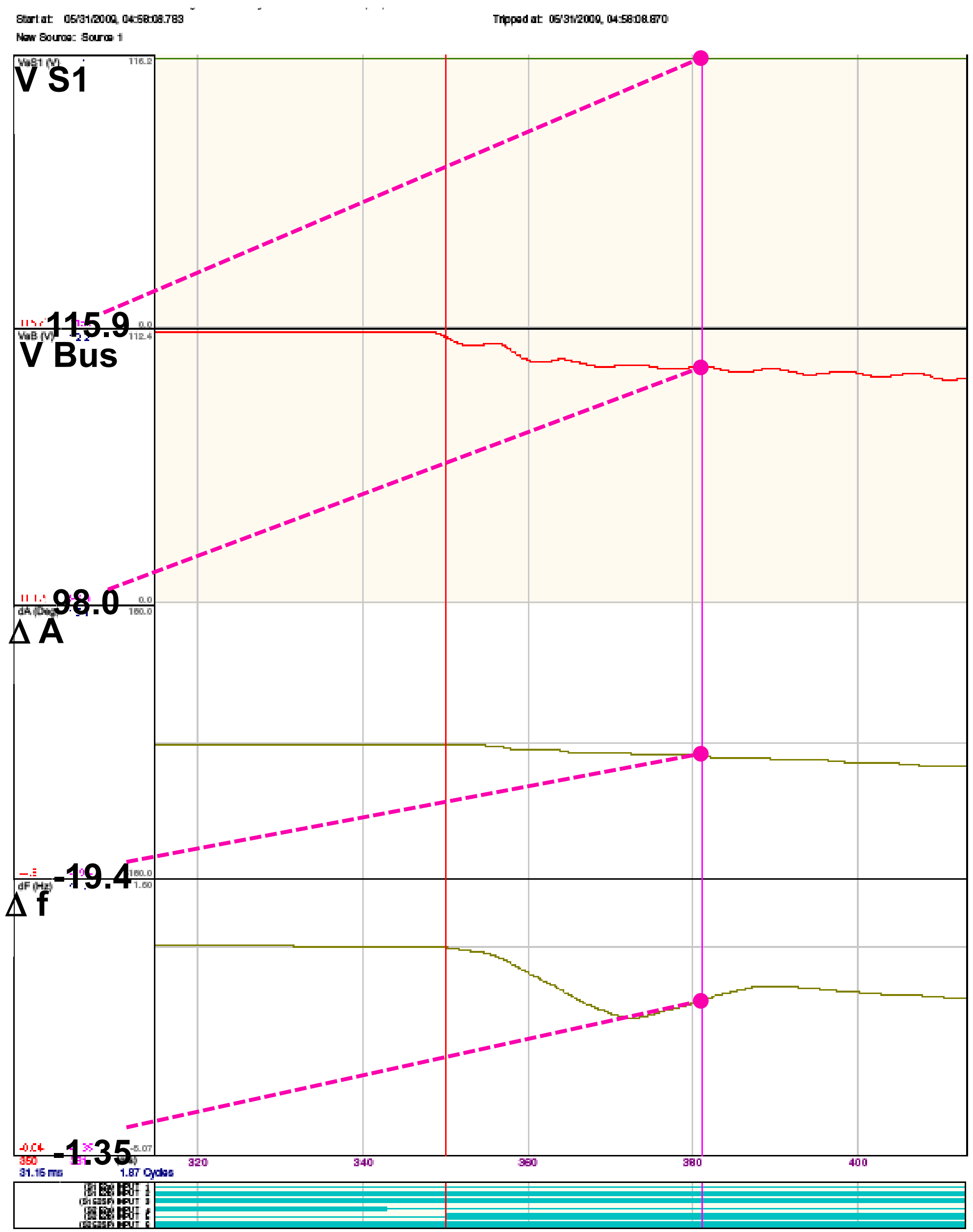
Close Command Issued

Source 1 = 115.9 Volts

Motor Bus = 98.0 Volts

Phase Angle = 19.4°

Delta Frequency = -1.35 Hz



Spin Down Analysis

Sequential Transfer Mode Fast Transfer Method Worst Case

New Source Breaker

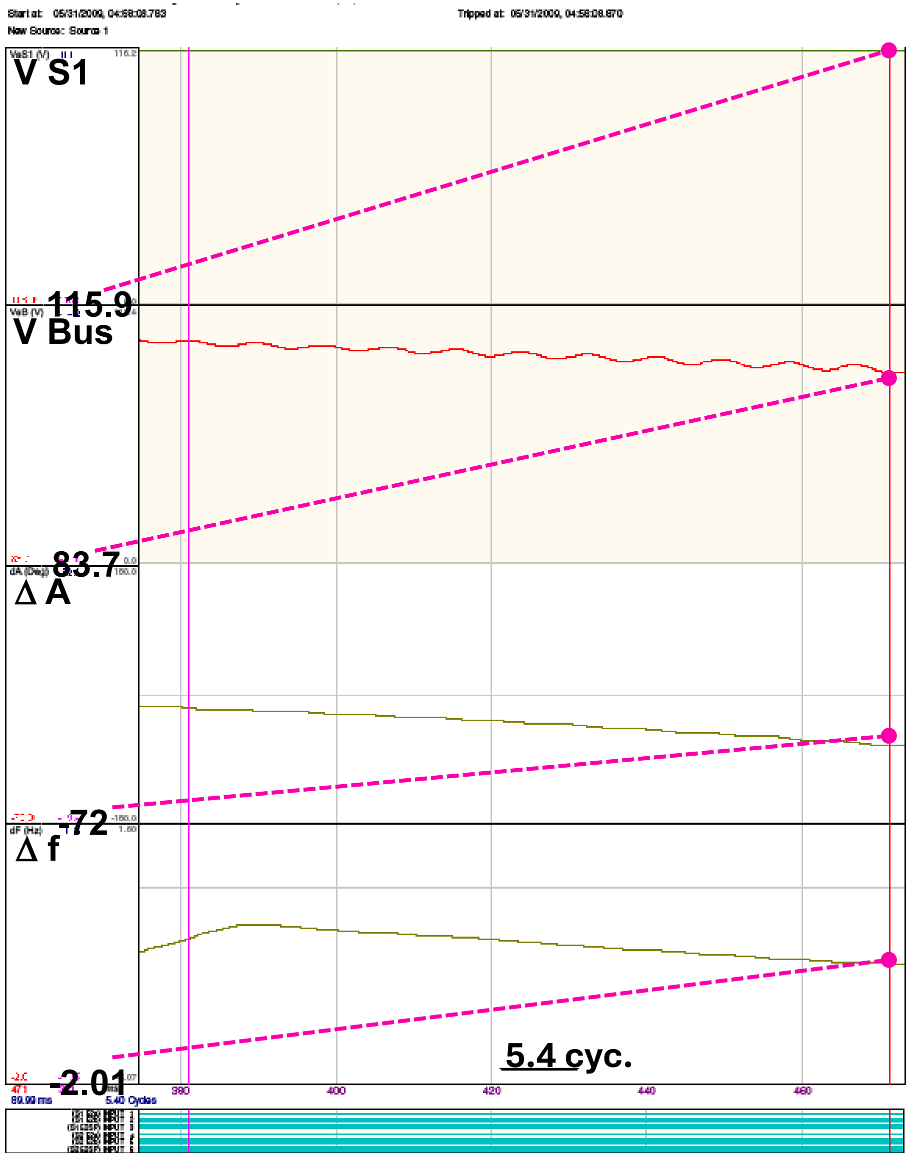
Close Command Issued

Source 1 = 115.9 Volts

Motor Bus = 83.7 Volts

Phase Angle = 72.0°

Delta Frequency = -2.01 Hz



Real Spin Down Analysis

Sequential Transfer Mode; Fast Transfer Method, Worst Case

- Phase angle = 72.0 degrees
- Motor bus pu voltage = 83.7/115.9 = 0.7222pu Vrms
- Motor bus pu frequency = (60-2.01)/60 = 0.9665pu Hz
- E_M = 0.7222/0.9665 = 0.7472pu V/Hz
- **E_R = 1.0471pu V/Hz**

  This E_R is higher than the 0.7719 V/Hz calculated above for the normal Sequential Fast Transfer but is within **ANSI/NEMA C50.41 limits.**

- Note that **during the 5.4 cycles** (90 ms) while the breaker is closing:
  - ✓ The motor bus has dropped **14.3 V.**
  - ✓ Delta Frequency between the motor bus and the new source has increased by **0.65 Hz.**
  - ✓ The Phase Angle difference has increased by **52.6 degrees.**

Real Spin Down Analysis

Determine Viability of Sequential Transfer with the In-Phase Method of Transfer

- Find the point when the old source “b” breaker status contact closes, confirming that the old source breaker has opened, and then determine when a Sequential Transfer would occur by the In-Phase Method of Transfer.
- The same per unit V/Hz calculation must now be performed for the Sequential In-Phase Transfer at the first zero crossing. Determine the first phase angle zero crossing between the motor bus and the new source.
- Determine the point 5.4 cycles to the left (the breaker closing time) to locate the point in time when the close command must be sent to the new source breaker.
- For a correct close at zero, the transfer system must send the close command at an advance angle before zero, taking into account the instantaneous slip frequency, the breaker closing time, the rate of change of slip frequency, and the angle change while the breaker is closing.

Spin Down Analysis

Sequential Transfer Mode In-Phase Transfer Method

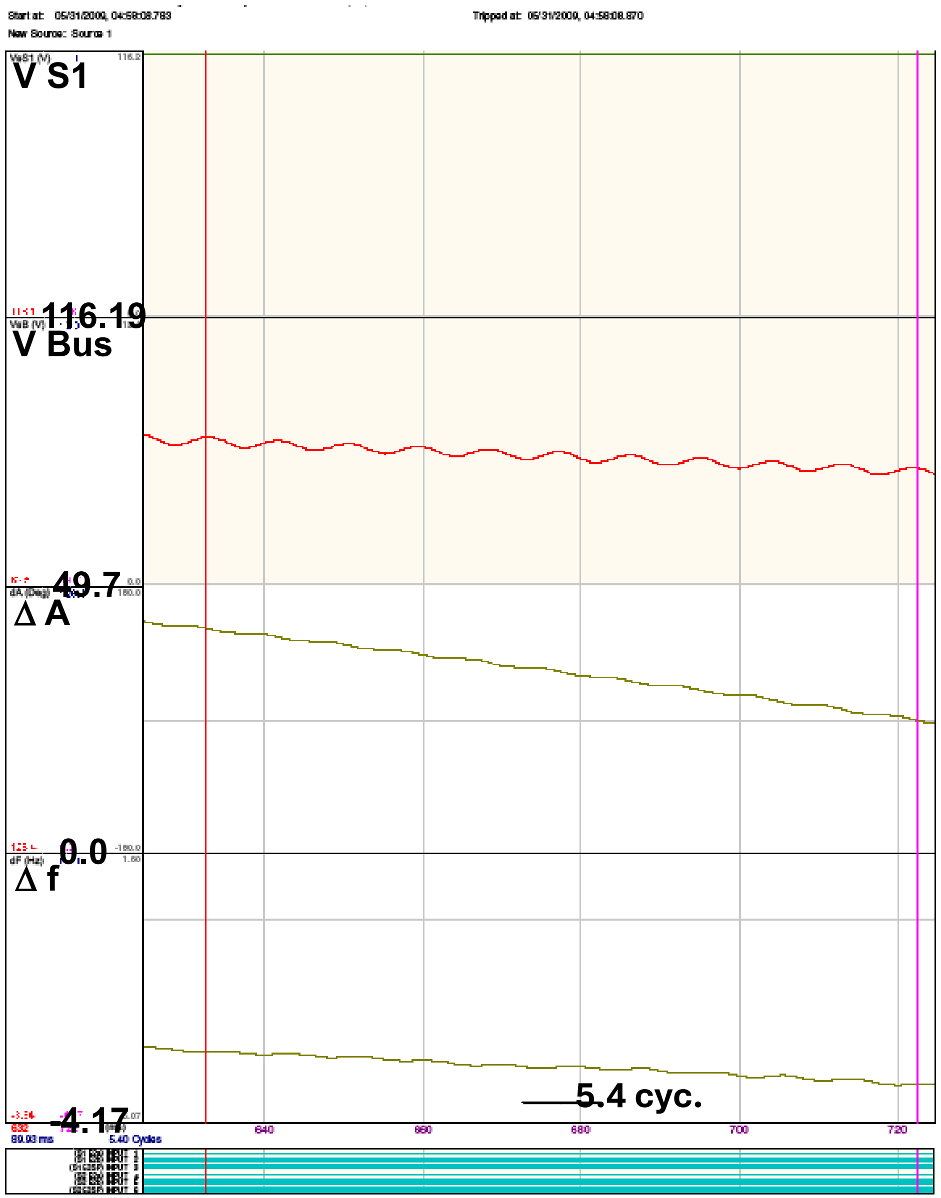
New Source Breaker Close

Source 1 = 116.1 Volts

Motor Bus = 49.7 Volts

Phase Angle = 0.0°

Delta Frequency = -4.17 Hz



Real Spin Down Analysis

Sequential Transfer Mode; In-Phase Transfer Method

- Phase angle = 0 degrees
- Motor bus pu voltage = 49.7/116.1 = 0.4281pu Vrms
- Motor bus pu frequency = (60-4.17)/60 = 0.9305pu Hz
- E_M = 0.4281/0.9305 = 0.4601pu V/Hz
- **E_R = 0.5399pu V/Hz**

  Again, this is well below the ANSI/NEMA Standard C50.41-2012 maximum Volts per Hertz due to the In-Phase breaker closure.

- Note that **during the 5.4 cycles** (90 ms) while the breaker is closing:
  - ✓ The motor bus has dropped **12.9 V to 49.7 V.**
  - ✓ The Delta Frequency between the motor bus and the new source has increased by **0.83 Hz** to 4.17 Hz.
  - ✓ The Phase Angle difference has decreased by **126.4** degrees.

Real Spin Down Analysis

Analysis of Oscillography to Determine Settings; Sequential In-Phase Transfer Setting Calculations

Important notes concerning ΔF Limit setting for the In-Phase Transfer Method:

- The transfer system must compare these settings to the predicted actual values of Delta Frequency at the point in time when the breaker contacts would be closing at the phase angle zero crossing.
- Thus, these settings are NOT compared to the ΔF Limit when the breaker close command is sent.
- This means the ΔF Limit setting must be set for the conditions at the point in time when the breaker closes.
- This predictive capability applies only to the In-Phase Transfer.

Real Spin Down Analysis

Analysis of Oscillography to Determine Settings; Sequential In-Phase Transfer Setting Calculations

- As previously determined, the ΔF between the motor bus and the new source at the point of the new source breaker closure at the first phase angle zero crossing between the motor bus and the new source is -4.17 Hz.
- Since this will have been predicted at the time of issuance of the breaker close command, the ΔF Limit setting must be set much greater than 4.17 Hz.
- Also, it was determined earlier that during the 5.4 cycles (90 ms) while the breaker is closing, the ΔF between the motor bus and the new source has increased by 0.83 Hz at a rate of 9 Hz / sec.

Except for extraordinary circumstances, the In-Phase Transfer Δf Limit setting should be set at its maximum 15.0 Hz so as not to block any In-PhaseTransfer.

Spin Down Analysis

Sequential Transfer Mode In-Phase Transfer Method

Time Between

Old Source

Breaker Opened

and

New Source

Breaker Close

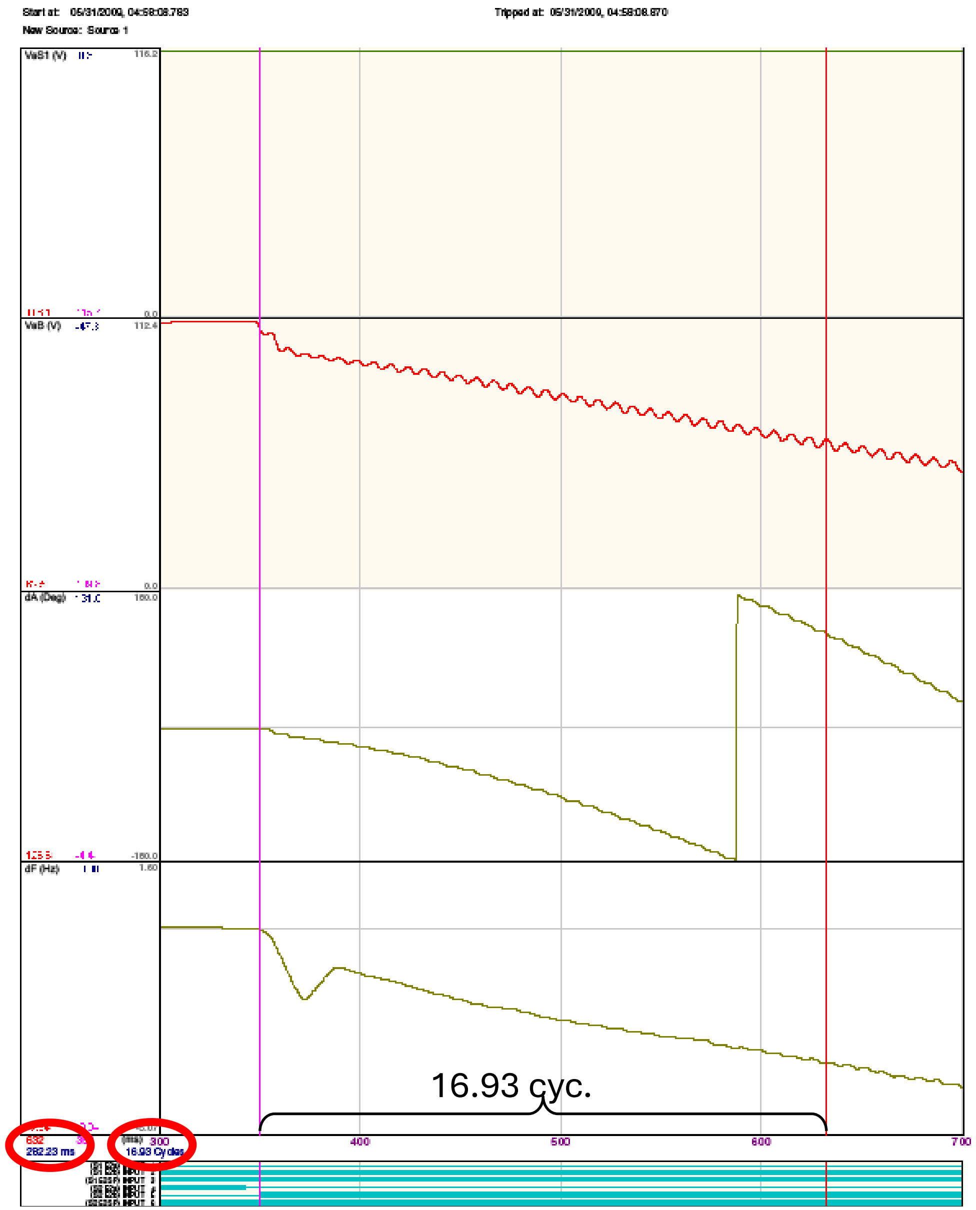
Issued

16.93 cycles or 282.23 ms

New Source

Breaker Closes

22.33 cycles or 372.23 ms



Real Spin Down Analysis

Analysis of Oscillography to Determine Settings; Sequential In-Phase Transfer Setting Calculations

- The Time Window for the Automatic In-Phase Transfer must be long enough to permit (not block) a legitimate In-Phase Transfer.
- The time between the point where the old source breaker “b” status contact closes, confirming that the old source breaker has opened, to the In-Phase Transfer breaker close command (5.4 cycles to the left of the first phase angle zero crossing) is 16.93 cycles or 282.23 ms after the transfer is initiated.
- Note that the ΔF Limit setting, not the Time Window, should be used to block In-Phase Transfers when the bus is decaying too rapidly.

The setting for the Time Window should be set well above this time, and since this really acts as an incomplete sequence timer, can probably be set for 120 cycles.

Motor Bus Transfer Application-The Need for Speed

Project Background

- Example with actual commissioning test data from at the Laguna II station in Mexico:
  - (2) combustion turbines (154MW)
  - (1) heat recovery steam plant (279MW)

The plant auxiliary loads :

- **Bus A (4KV)**
- 3600HP High pressure boiler feed pump
- 3600HP High pressure boiler feed pump
- 1100HP Condensate pump
- 620HP Closed circuit Cooling pump
- 1500HP Gas compressor
- 450HP Auxiliary cooling pump
- 480V Service Transformers

- **Bus B (4KV)**
- 3600HP High pressure boiler feed pump
- 3600HP High pressure boiler feed pump
- 1100HP Condensate pump
- 620HP Closed circuit Cooling pump
- 1500HP Gas compressor
- 1500HP Gas compressor
- 450HP Auxiliary cooling pump
- 480V Service Transformers

Motor Bus Transfer Application-The Need for Speed

Transfer Data Analysis

Simultaneous Mode

Transfer Time: (both breakers open)	24.2mSec
Transfer Angle:	11.7deg
Bus Voltage at Transfer:	98.2/120V
Bus Frequency at transfer:	58.4Hz
V/Hz per C50.41-2000	**0.246pu**

Sequential Mode

Transfer Time: (both breakers open)	79.1mSec
Transfer Angle	38.2deg
Bus Voltage at Transfer:	77.8/120V
Bus Frequency at transfer:	57.8Hz
V/Hz per C50.41-2000	**0.629pu**

The sequential transfer was slower which allowed the motor bus frequency and voltage to decay further, however the V/Hz quantities are far below the 1.33pu limit.

Even in this application, which has less than ideal mechanical inertia, the sequential mode offers significantly more security without compromising the transfer.

In applications with faster vacuum breakers, there will be even less difference between sequential and simultaneous operating modes.

Motor Bus Transfer Application-The Need for Speed

Issues with Traditional Sync Check Relays-Why the Need for Speed?

- Using traditional sync check relays, measurement time is very slow (up to 100mS)
  - Long measurement time prevents the traditional scheme from detecting unacceptable conditions which result in an improper transfer
- In an attempt to minimize this effect, traditional transfer systems are designed to operate at the highest possible speed in the simultaneous mode
- The safety of the simultaneous mode relies on a fast and reliable breaker failure scheme.
  - Frequently, breaker failure schemes are nonexistent or are assembled from auxiliary relays and wiring that are rarely tested

High Speed Sync Check Relays with ultra high speed permissive and blocking response characteristics allow the LUXURY of using the sequential mode and waiting until the old source breaker is open before permitting or correctly blocking a sync check supervised close command to the new source.

MBT Performance Test Protocols

- The electric power industry presently has no industry standards on the performance requirements for relays used to supervise critical process motor bus transfers.
- A device-testing protocol was proposed in the 2012 IEEE Power System Relaying Committee Report for sync check relays used to implement motor bus fast transfer.
- The same 2012 IEEE PSRC Report included a device-testing protocol for undervoltage relays used to implement motor bus slow residual voltage transfer.
- An expanded test protocol is now proposed for relays used to implement motor bus synchronous transfer (Fast and In-Phase), and the results of this extensive performance testing are analyzed per the requirements of ANSI/NEMA C50.41-2012.

Motor Bus Transfer Success Criterion

ANSI/NEMA C50.41 vs. Torque Ratio

- Case studies of a number of live motor bus transfers are analyzed to assess a new transfer criterion that better represents transient currents and torques.
- The industry ANSI/NEMA C50.41 Standard criteria, calculated at the instant of transfer, presently used for determining the success of a completed transfer, are discussed and critiqued.
- A new transfer metric is derived, based on the ratio of the aggregate peak torque after transfer to the aggregate load torque prior to transfer.
- The industry ANSI/NEMA C50.41 Standard per unit Volts per Hertz metric is discussed in light of the results of the new torque ratio metric.

New Metric for Assessing MBT

- The pu V/Hz calculation depends on only three values at closure compared to the new source: the bus voltage difference, frequency difference, and 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 ignores current, it cannot possibly address the torques motors are experiencing. Therefore, use of the 1.33 pu V/Hz limit at breaker close as a criterion for the safe transfer of motor buses leaves room for improvement.
- The FACILITY 1 through 36 oscillographic records of live motor bus transfers will now be analyzed to derive a new transfer metric, based on a torque ratio at the close of the new source breaker.
- The voltage and current during inrush will be measured in the time domain and employed to calculate the resultant peak torque at transfer as a multiple of load torque prior to transfer as if the aggregate bus were a single induction motor drawing the same current and power.

Motor Torque Calculation

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

$T = P_{AG}/\omega_S$
Assumes all losses (copper, iron, friction, and windage losses) are neglected.

The air gap torque is calculated for two different conditions:

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

The Torque Ratio provides a normalized way of looking at transient torque during motor bus transfer.

Air Gap Torque Calculation

- In order to calculate the Torque, the power drawn by the motor needs to be calculated which requires voltage and current phasors.
- Recursive discrete Fourier transform is used to calculate the voltage and current phasors:

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

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

Where v_k *and* i_k *are the sampled values of voltage and current signals*
N (=32) is the number of samples/cycle

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

Air Gap Torque Calculation

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

$$S_k = P_k + jQ_k = 3\ V\ I^* = 3\ (V_k^r + j\ V_k^i)\text{x}\ (I_k^r - j\ I_k^i)$$

The real power (P_k) is given by: $P_k = 3\ (V_k^r\ I_k^r + V_k^i\ I_k^i)$

When three phase sampled values are available, the power can be computed as follows:

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

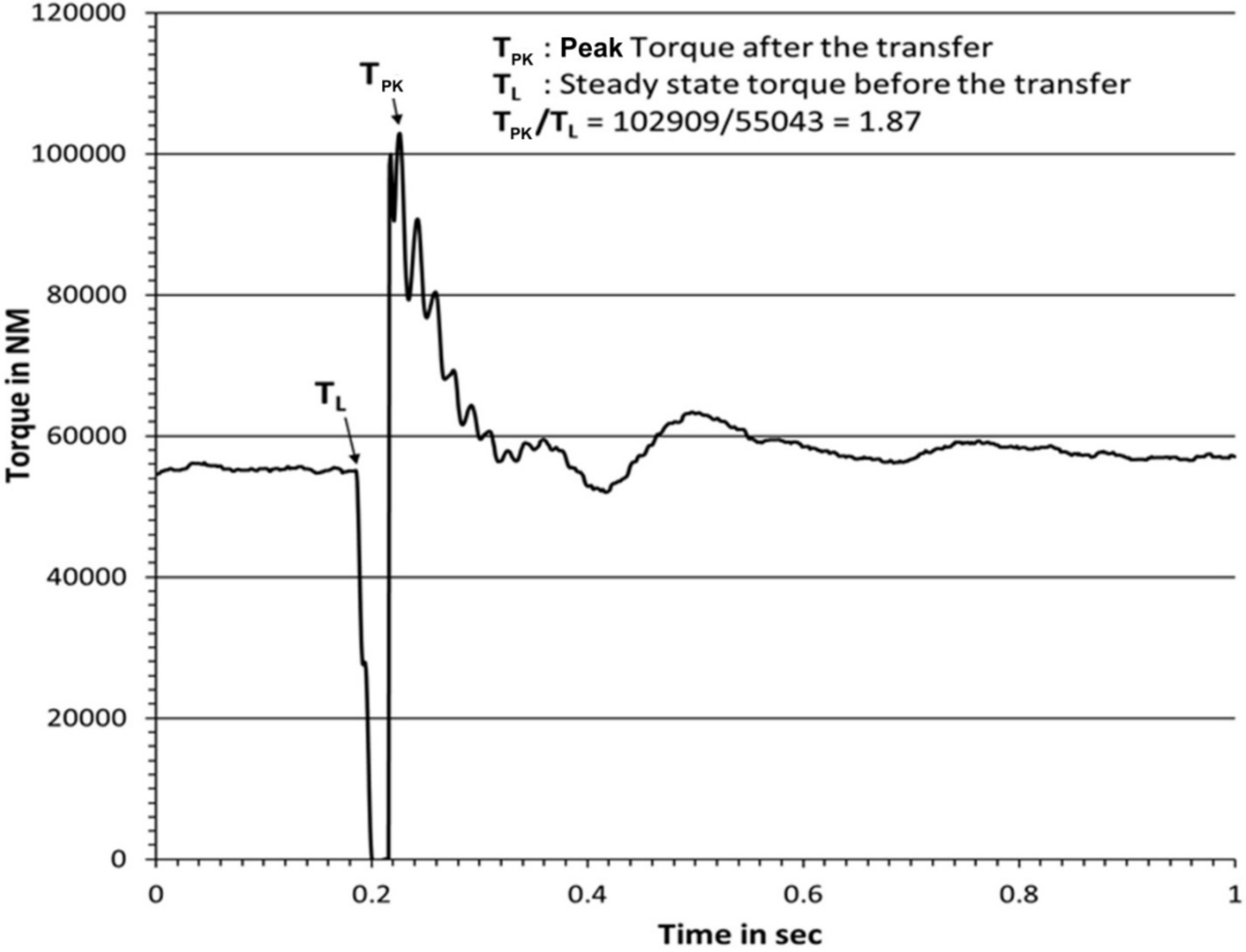
Air Gap Torque Calculation

- Stator core and copper losses are neglected
- The Power P_k can be considered as the power transmitted through the air gap
- The air gap torque at k_{th} instant is calculated as follows:

$$T_k = P_k / \omega_s$$

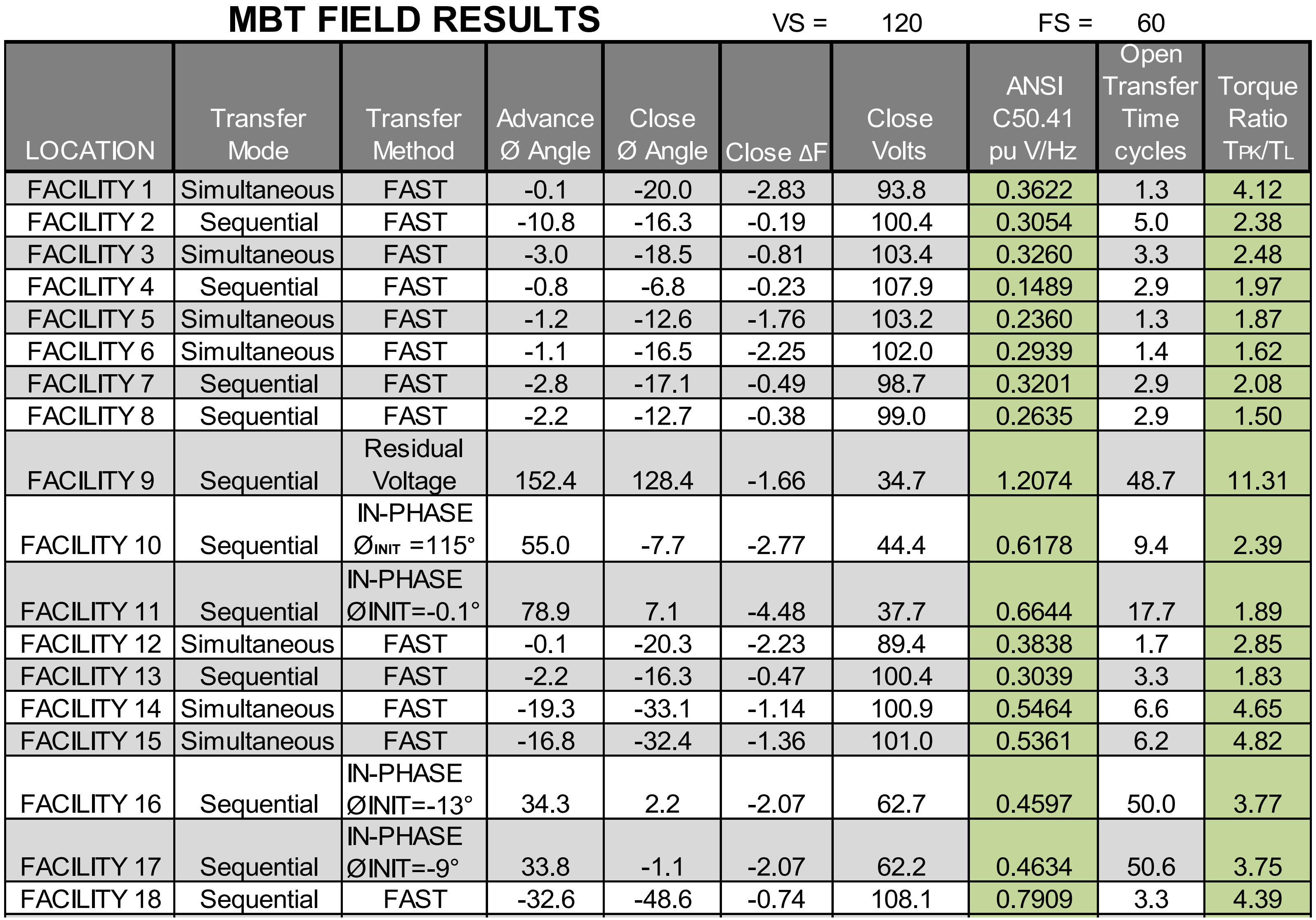
where ω_s *is the synchronous speed in radians per second*

Motor Air Gap Torque, Before and After Transfer



On-Site Live MBT Field Results

Live Open Transition Transfers Under Normal Operating Load Conditions

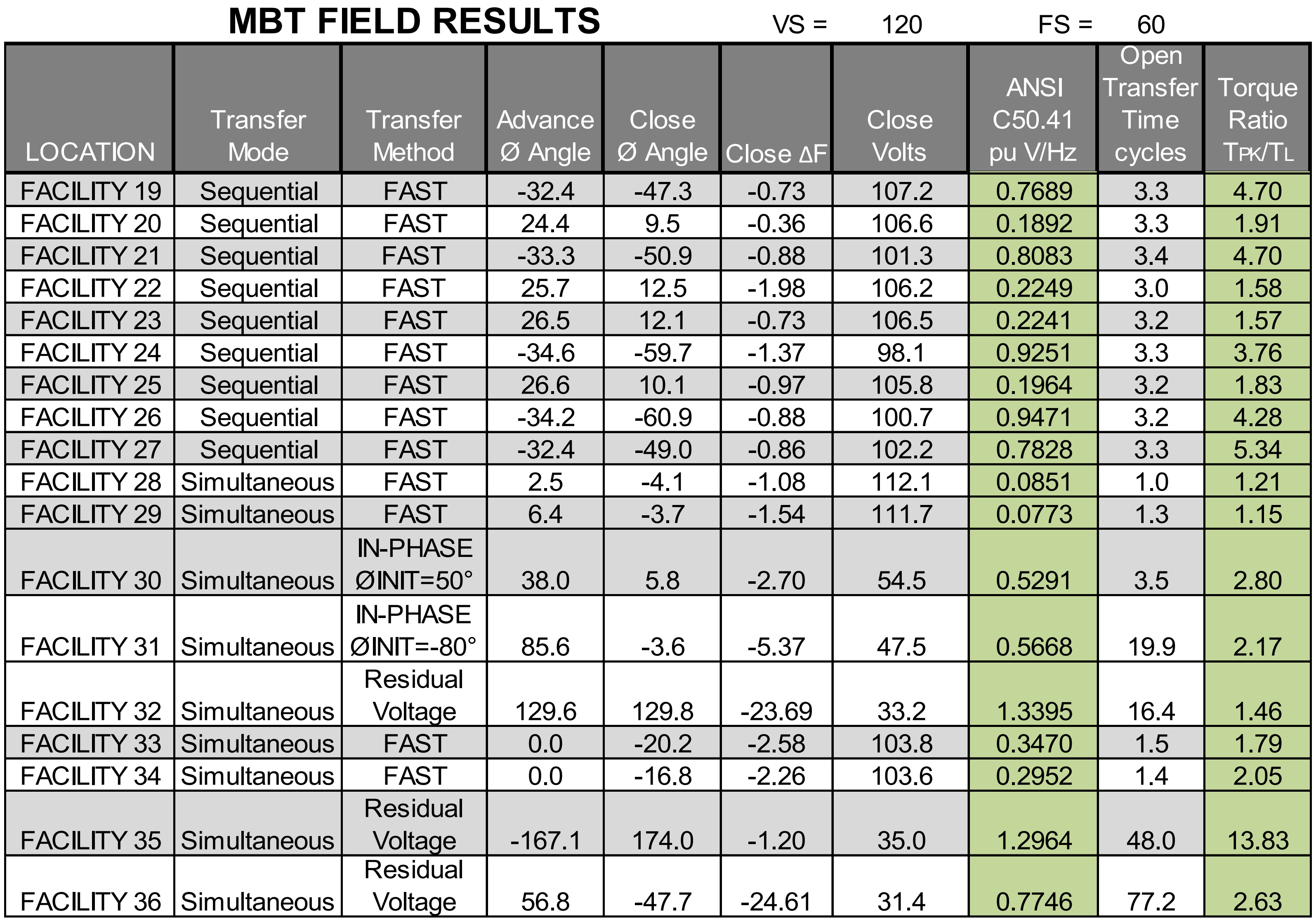


MBT FIELD RESULTS VS = 120 FS = 60

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

Onsite Live MBT Field Results

Live Open Transition Transfers Under Normal Operating Load Conditions



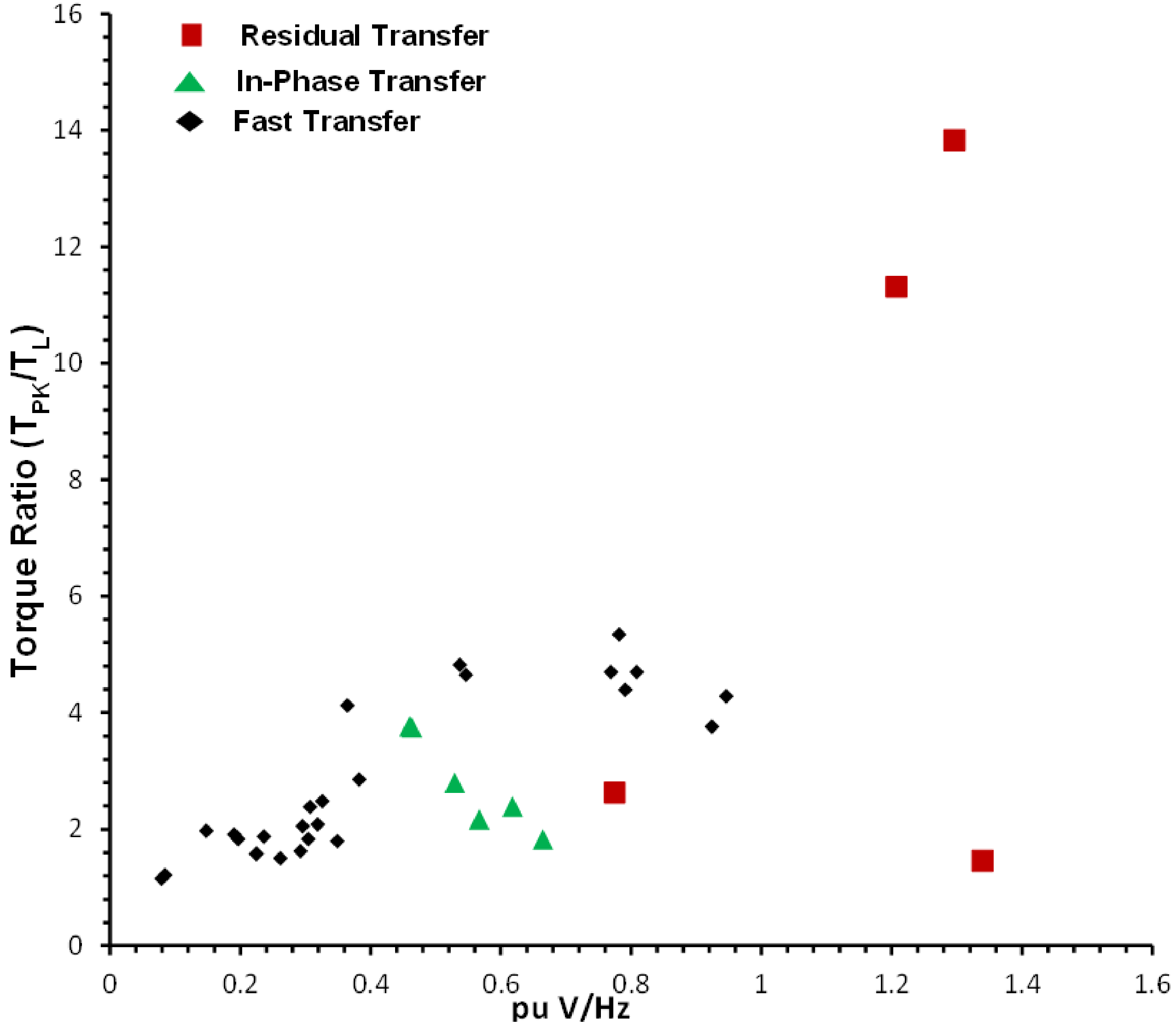
MBT FIELD RESULTS VS = 120 FS = 60

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 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

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

Torque Ratios (TPK/TL) vs. pu V/Hz



Fast and In-Phase Synchronous Transfer Results

- Fast Transfers occurred in 26 instances, all completed between 0.0773 (FACILITY 29) and 0.9471 pu V/Hz (FACILITY 26), well under the ANSI/NEMA C50.41 limit of 1.33 pu V/Hz.
- 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.
- In-Phase Transfers occurred in 6 instances, all completed between 0.4597 (FACILITY 16) and 0.6644 pu V/Hz (FACILITY 11), well under the ANSI/NEMA C50.41 limit of 1.33 pu V/Hz.
- The six In-Phase Transfers occurred with Torque Ratios between 1.89 (FACILITY 11) and 3.77 (FACILITY 16).
- All 32 Synchronous Transfer breaker close commands occurred at voltages above which the Residual Voltage Method would have operated.

Observations

ANSI/NEMA C50.41 pu V/Hz vs. Motor Torque Ratio T_{PK}/T_L

- There is low correlation between pu V/Hz and Torque Ratio.
- In-Phase Transfer cases (Facilities 10, 11, 16, 17, 30 and 31) have higher pu V/Hz than most of the Fast Transfer cases, but do not have higher Torque Ratios (T_{PK}/T_L). In fact, Torque Ratios for the In-Phase Transfers fall right in the middle of the Torque Ratios for all the Fast Transfers.
- ANSI/NEMA C50.41 states that out-of-phase bus transfers develop transient currents and torques that may range from 2 to 20 times rated. Facility 35 results demonstrate this with a Torque Ratio of 13.83 for a Residual Voltage Transfer close at 174.0 degrees.
- Yet the ANSI/NEMA C50.41 pu V/Hz limit of 1.33 would give this Residual Voltage Transfer a passing grade at 1.2964 pu V/Hz.

Residual Voltage Transfer 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

- Residual Voltage Transfers occurred at 3 facilities (9, 35 and 36) when the Synchronous Transfer Methods were purposely disabled, so the results for a Residual Voltage Transfer could be observed.
- The Close Voltages were about the same. FACILITIES 9 and 35 had little frequency decay but significant closing angles, compared with significant frequency decay and a small closing angle at FACILITY 36.
- Clearly the high closing angles correlate with the high Torque Ratios, while the pu V/Hz metric still gives these hard transfers a passing grade.
- Results at FACILITIES 9 AND 35 demonstrate unsafe high Torque Ratios at 34.7 Vac and 35.0 Vac, nearly at 1.5 times the open-circuit AC time constant value, the alleged “safe” zone.

Facilities 11 Compared TO 9 and 35

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

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

Facilities 11, 16 and 17

Successful In-Phase Transfers Completed After Blocked Fast Transfers

- In-Phase Transfer cases from Facilities 11, 16 and 17 all have a small initial phase angle difference, so a Fast Transfer would have been successful. However, in all three cases, the Fast Transfer method was blocked, and the transfer was completed by the In-Phase Transfer method.
  - FACILITY 11: The Fast Transfer method was disabled intentionally in order to evaluate the performance of the In-Phase Transfer.
  - FACILITY 16: The initial phase angle was -13°, but Sequential Transfer mode prevented closing the new source breaker until the old source breaker tripped. This was fortuitous as the old source breaker did not trip for 12 cycles, while the phase angle between the motor bus and the new source advanced from -13° to -55°, blocking Fast Transfer when the breaker finally opened.
  - FACILITY 17: Conditions again required the use of the Sequential Transfer mode. Similar to FACILITY 16, as an upstream breaker tripped, the old source breaker took 17 cycles to open as the phase angle difference increased from -9° to -77°, blocking Fast Transfer.

Facilities 11, 16 and 17

Successful In-Phase Transfers

In-Phase Transfer operations from cases 16 and 17 clearly demonstrate the value of In-Phase Transfer when a Fast Transfer is blocked due to loss of an upstream source, coupled with the slow trip time of the faulty old source breaker.

FACILITY 11 In-Phase	FACILITY 16 In-Phase	FACILITY 17 In-Phase
37.7 Vac	62.7 Vac	62.2 Vac
-4.48 Hz	-2.07 Hz	-2.07 Hz
7.1°	2.2°	-1.1°
Transfer=17.7 cycles	Transfer=50.0 cycles	Transfer=50.6 cycles
0.0644 pu V/Hz	0.4597 pu V/Hz	0.4634 pu V/Hz
Torque Ratio=1.89	Torque Ratio=3.77	Torque Ratio=3.75

Motor Torque Ratio T_{PK} /T_L Conclusions

- 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.
- Some transfers with low Torque Ratios are given much higher pu V/Hz values than others with relatively equal Torque Ratios.

Motor Torque Ratio T_{PK} /T_L Conclusions

- ANSI/NEMA C50.41 pu V/Hz is not a good measure of motor torque.
- ANSI/NEMA C50.41 advice that “Slow transfer or reclosing can be accomplished by a time delay relay equal to or greater than 1.5 times the open-circuit alternating-current time constant of the motor” is wrong. Torque is NOT within acceptable levels at large close angles, even at low voltage.
- Motor Torque Ratio (T_{PK} /T_L) 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 Torque Ratio criterion can be used to calculate both aggregate and individual motor torque (in per unit of max rated torque) at transfer.
- Residual Voltage Transfer where the phase angle and slip frequency are ignored can produce dangerously high torques.
- 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.
- This is due to lower real power exchange between the new source and the motor as a result of the In-Phase near-zero phase angle difference at transfer.

Motor Modeling - Transient Current & Torque

- Model three motors of various sizes, inertia, impedance, and loads connected on a single motor bus to calculate the peak transient motor current and torque at transfer (pu of motor rated).
- Using Residual Voltage Transfer, study the effect of different breaker closing phase angles on the individual peak transient current and torque for each of the motors immediately following the closure of the backup source breaker.
- Individual motors exhibit positive and negative transient torques, oscillating from induction generator to motor, and the peak-to-peak torques are also recorded, as they will impact the motor windings, bearings, couplings, gear box and shaft torsion.

Motor Modeling - Transient Current & Torque

Modeling Applied to the Following Operating Conditions:

- Normal Across-the-Line Motor Start.
- Three-Phase Fault on the Motor.
- In-Phase Transfer.
- Residual Voltage Transfer, Closing at Various Phase Angles.

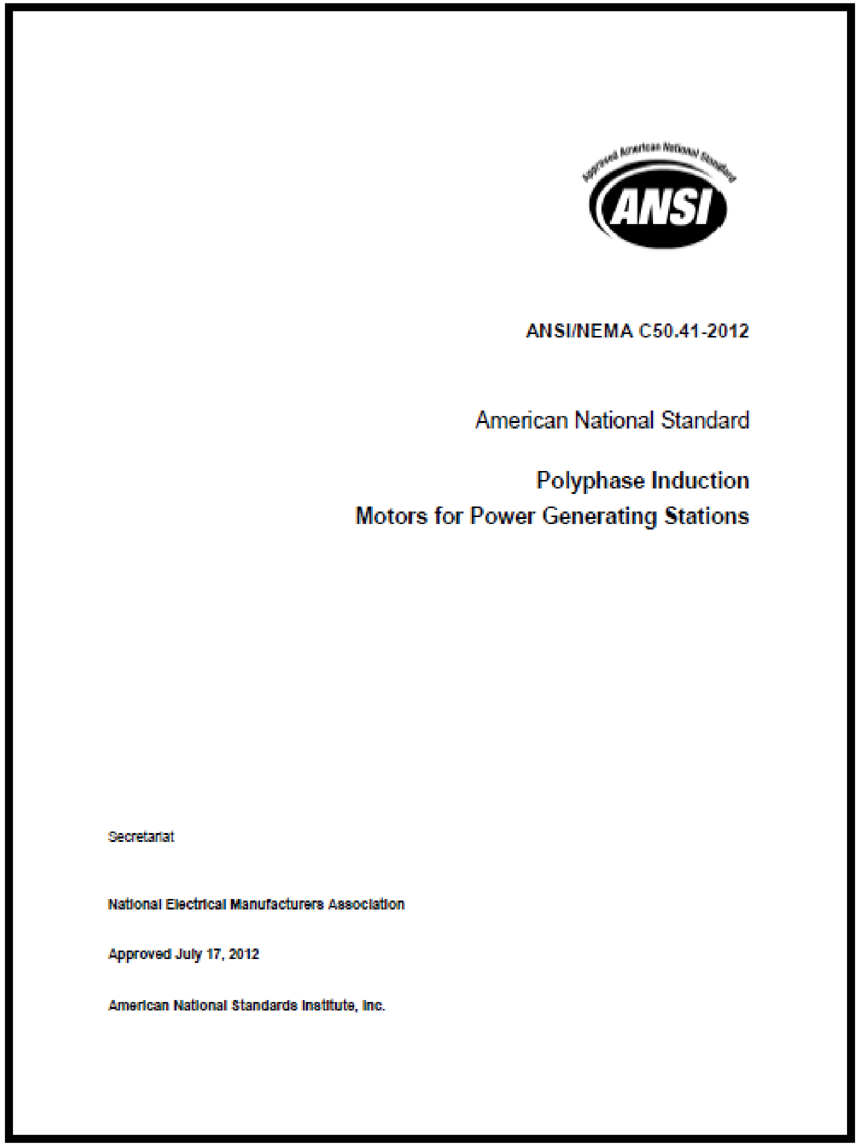
Motor Modeling - Transient Current & Torque

Analysis of the Results of the Modeling

- Analyze the severity of the resultant individual motor torques and currents to determine if levels have been exceeded that could cause cumulative damage and loss of life to motors and connected equipment.
- Based on the levels of torques measured, the efficacy of the transfer criteria found in ANSI/NEMA C50.41 will be brought into question.

ANSI/NEMA Standard C50.41-2012

Polyphase Induction Motors for Power Generating Stations



ANSI/NEMA C50.41-2012

American National Standard

Polyphase Induction
Motors for Power Generating Stations

Secretariat

National Electrical Manufacturers Association

Approved July 17, 2012

American National Standards Institute, Inc.

ANSI/NEMA STANDARD C50.41-2012

General

- 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.
- Transient current and torque may range from 2 to 20 times rated … subjects the motor (including the motor windings) and driven equipment to transient forces in excess of normal running values.
- Reduces the life expectancy of the motor by some finite value.

ANSI/NEMA STANDARD C50.41-2012

Slow Transfer or Reclosing

- To limit possibility of damaging the motor or driven equipment... the resultant volts per hertz at transfer doesn’t exceed 1.33 pu V/Hz
- Delayed until motor rotor flux linkages decayed… accomplished by a time delay equal or greater than 1.5 times the open-circuit AC time constant of the motor [22.3% of rated bus voltage or 26.8 Vac on 120 Vac PT]

ANSI/NEMA STANDARD C50.41-2012

Fast Transfer or Reclosing

- Occurs within a time period of 10 cycles or less.
- The resultant volts per hertz at the instant of transfer does not exceed 1.33 pu V/Hz.

Motor Model Description

- The voltages and currents in the simulation are transformed from instantaneous values in the abc system to dq frame using the Clarke transformation.
- The stator core losses are neglected here to simplify the circuit representation.

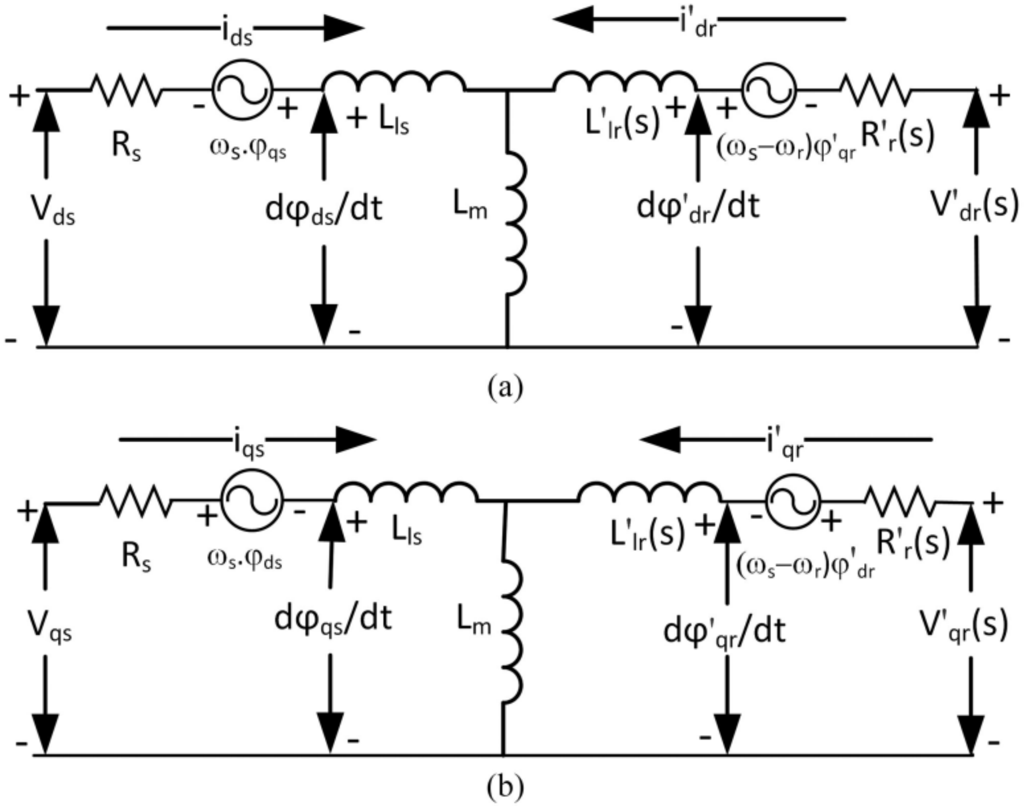
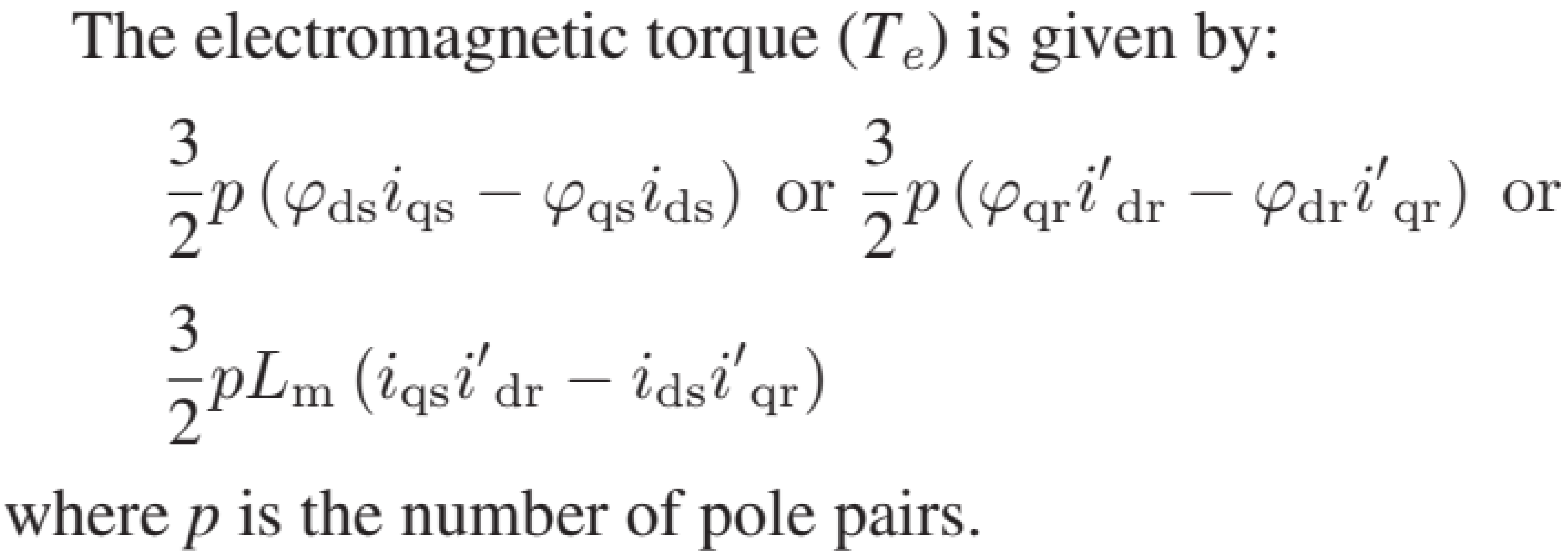


Fig. 1. *dq* model equivalent circuits of an induction motor. (a) *d*-axis and (b) *q*-axis.

Motor Model Description

- The electromagnetic torque(T_e) transferred through the airgap is given by either stator or rotor flux linkages and the corresponding currents:



The electromagnetic torque (T_e) is given by:

$$\frac{3}{2}p\left(\varphi_{\mathrm{ds}}i_{\mathrm{qs}}-\varphi_{\mathrm{qs}}i_{\mathrm{ds}}\right)\ \text{or}\ \frac{3}{2}p\left(\varphi_{\mathrm{qr}}i'_{\mathrm{dr}}-\varphi_{\mathrm{dr}}i'_{\mathrm{qr}}\right)\ \text{or}$$

$$\frac{3}{2}pL_{\mathrm{m}}\left(i_{\mathrm{qs}}i'_{\mathrm{dr}}-i_{\mathrm{ds}}i'_{\mathrm{qr}}\right)$$

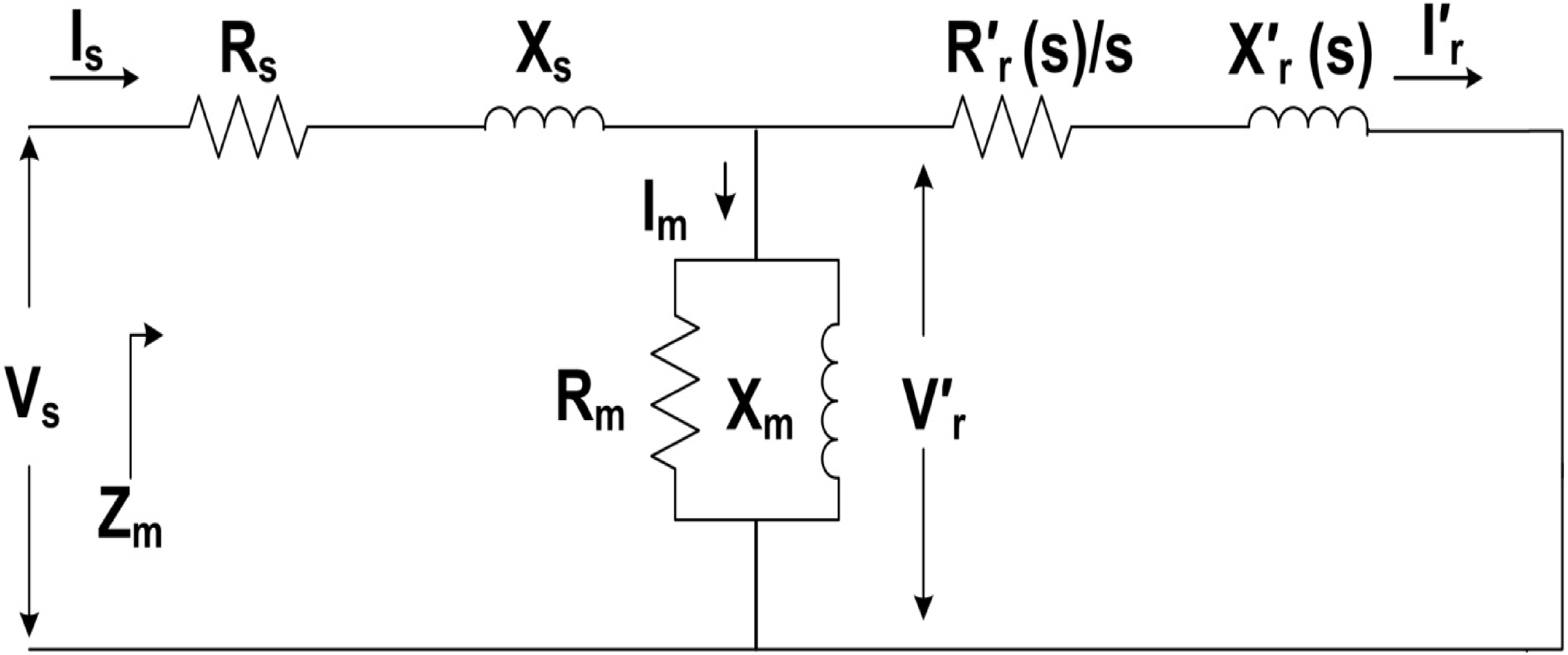
where p is the number of pole pairs.

Slip Dependency of the motor parameters

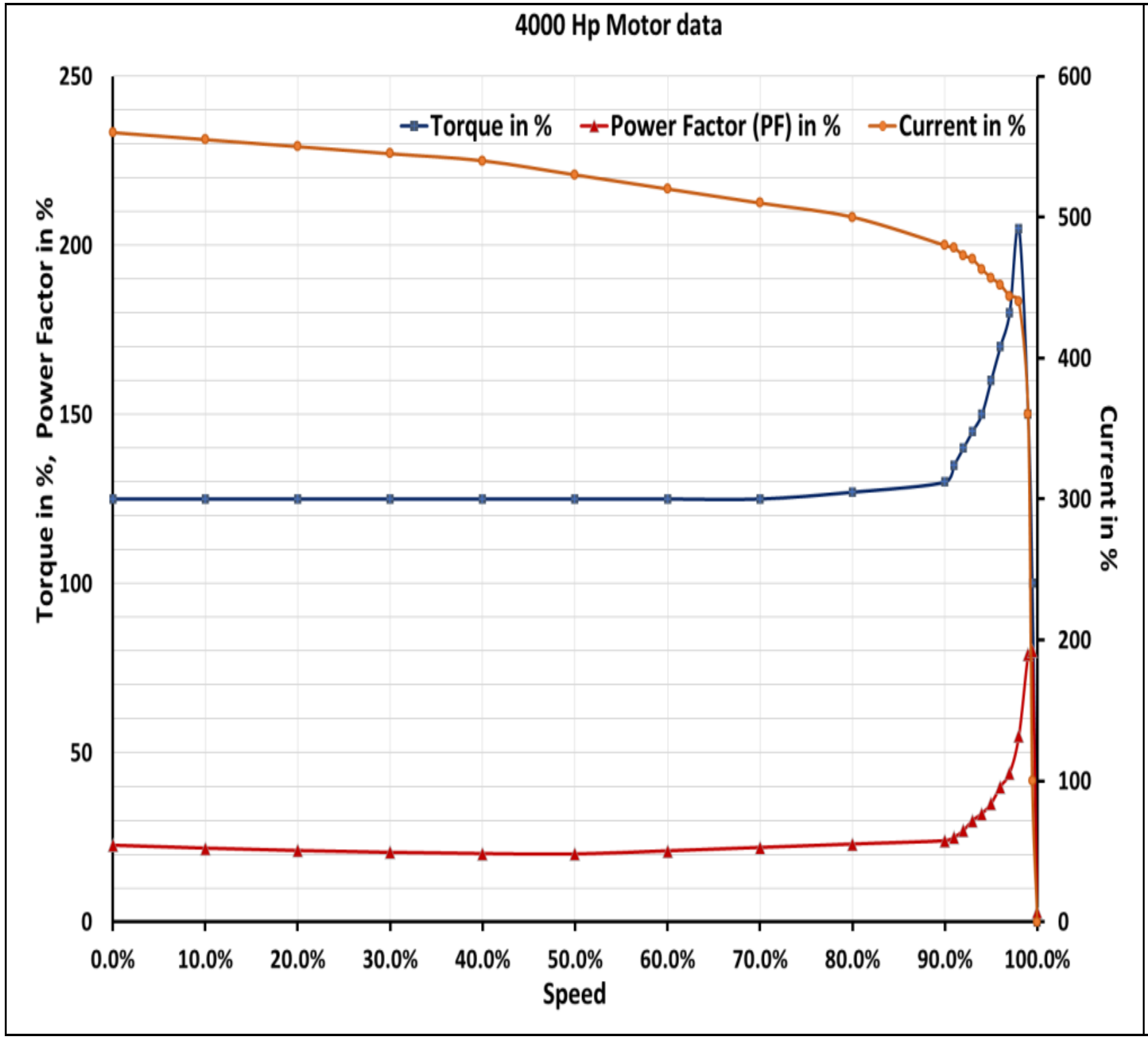
- The dependency of rotor impedance to rotor speed is not a linear relation.
- The slip vs. torque, slip vs. efficiency and slip vs. PF curves are used to calculate the rotor resistance and reactance.

Motor Model Description

- For the purpose of calculating rotor parameters with slip dependency, the following induction motor circuit representation is used:



Motor Model Description



Motor Parameter Estimation Modeling

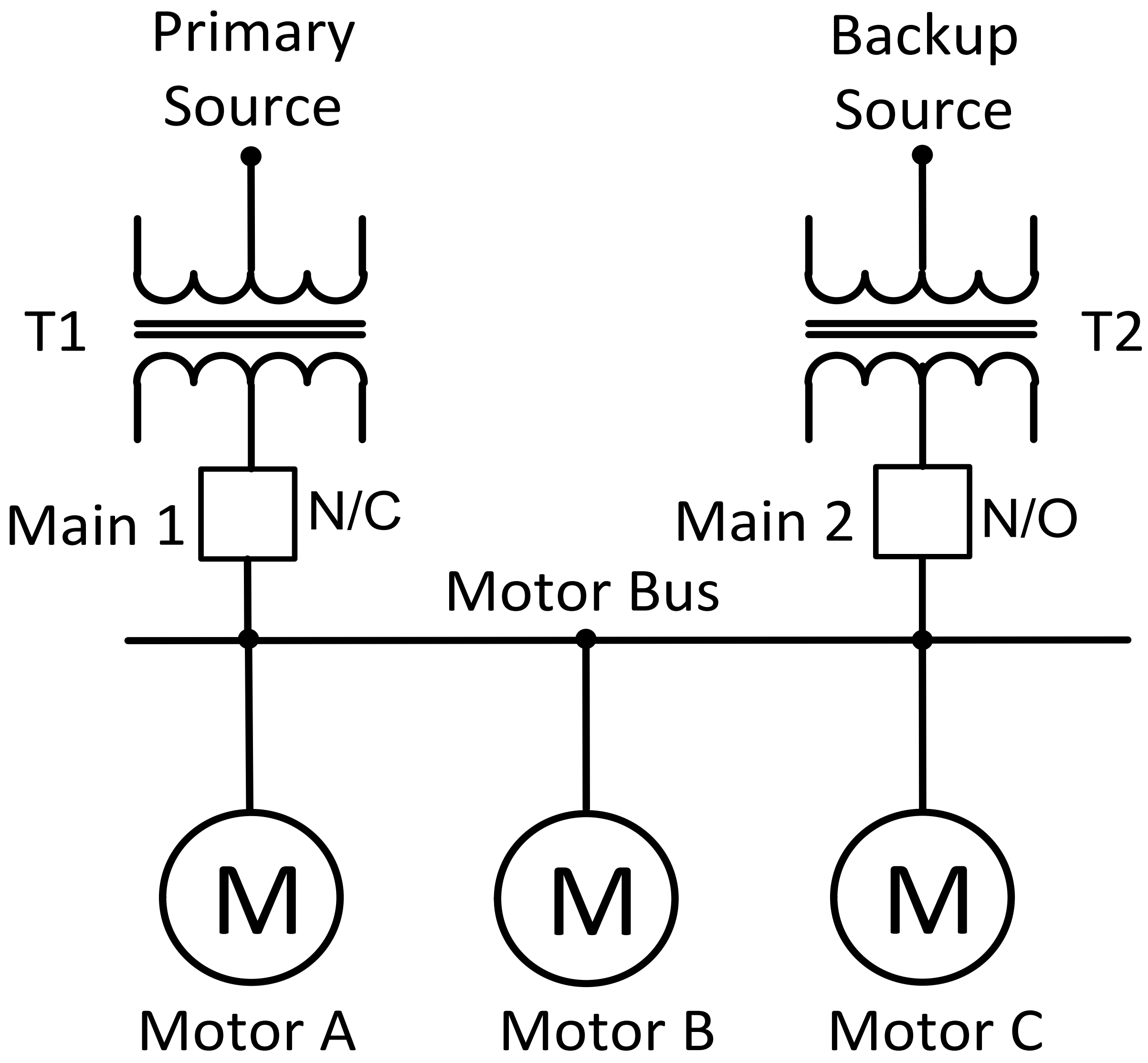
Circuit parameters (refer to Fig. 2)

R_s = 0.66%
X_s = 15.06%
R_m = 4043%
X_m = 383%
R_r (lr) = 3.4%
X_r (lr) = 2.23%
R_r(fl) = 0.56%
X_r(fl) = 11.92%

Calculated slip dependency parameters

Slip (%)	R_r (%)	X_r (%)
100.00	3.40	2.23
90.00	3.38	3.06
80.00	3.33	3.94
70.00	3.20	4.77
60.00	2.91	5.59
50.00	2.50	6.41
40.00	2.15	7.22
30.00	1.79	8.37
20.00	1.43	9.87
10.00	0.86	10.94
9.00	0.86	11.46
8.00	0.86	11.98
7.00	0.86	12.41
6.00	0.84	12.53
5.00	0.79	12.29
4.00	0.74	11.95
3.00	0.69	11.61
2.00	0.60	11.42
1.00	0.57	11.76
0.56	0.56	11.92
0.00	0.54	12.10

The Motor Bus



The Motor Bus and Motor Details

- The motor bus is supplied via 13.8/4.16 kV (20 MVA, Z=5%) Transformers T1 and T2.
- Each motor is modeled based on available motor data, as three motors with different sizes and loads have been chosen to represent an example of an industrial power system.

MOTOR	POWER	VOLTAGE	# POLES	LOAD	% LOAD
A	4000 hp	4 kV	4-pole	2500 kW compressor	76.90%
B	1500 hp	4 kV	2-pole	1000 kW induced draft fan	85.20%
C	500 hp	4 kV	6-pole	300 kW pump	78.80%

Why Perform Residual Voltage Transfer Tests Closing at Various Phase Angles?

- At transfer initiate, the initial phase angle may be nowhere near zero!
- So, at the end of a Residual Voltage Transfer spin down, the close phase angle may be nowhere near zero!
- ANSI/NEMA Standard C50.41-2012 confirms that, “test conditions should account for any phase angle difference between the incoming and running power supplies.”

Tests Performed Under the Following Operating Conditions

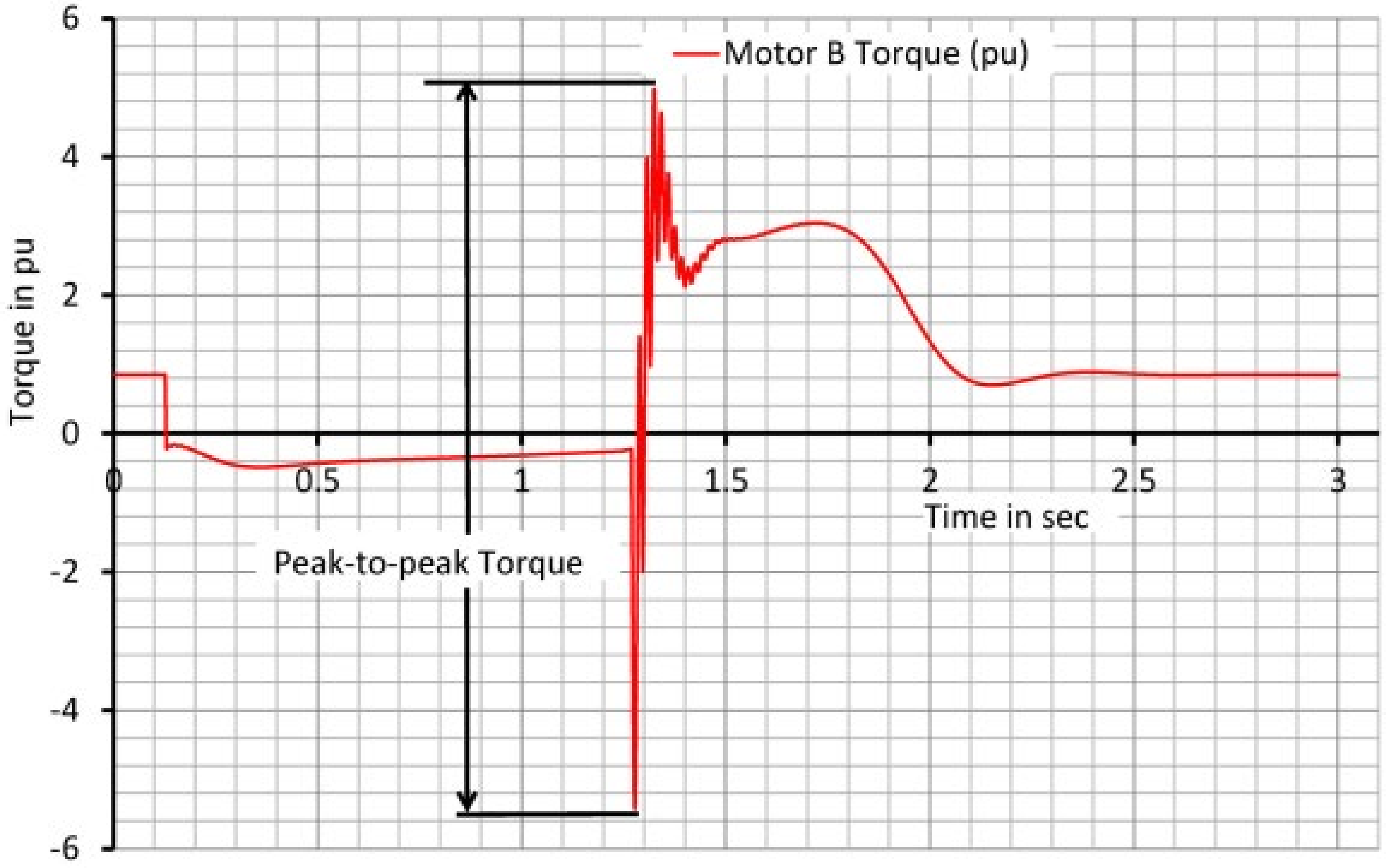
- **Normal Across-the-Line Motor Start** - Induction motors experience high stator current and torque during motor start and are designed to sustain this condition for short periods of time. The model includes starting parameters: locked rotor current and breakdown torque.
- **Three-Phase Short Circuit on Motor Terminals** - Torque can be great enough to overstress motor mounts to foundation or damage drive train shafts and couplings. Typically, a specified maximum value of six times rated torque.
- **In-Phase Transfer** - ANSI C50.41 limits Fast Transfers to “10 cycles or less”, so a worst case In-Phase Transfer test is performed that takes longer than 10 cycles to rotate 330° to the first pass through zero degrees to complete a smooth synchronous transfer.
- **Residual Voltage Transfer** - Tests are performed with initial phase angles varied between primary and backup sources, resulting in varied closing phase angles on completion of transfer.

Residual Voltage Transfer Test And Measurement Methodology

- The initial angle is varied by 30 degree steps.
- Transfer is initiated, opening the Primary Source breaker, and the motor bus voltage and frequency decays.
- During spin down, each of the three motors can be in generation mode (negative torque) or motor mode (positive torque) depending upon inertia of the motors.
- The breaker close command is sent to the Backup Source breaker when the motor bus voltage reaches 30% with breaker close <30%.
- After breaker closure, peak current and peak positive, peak negative and peak-to-peak transient torques are measured.

NOTE: Transient peak-to-peak torque is defined as the difference between the positive peak and the negative peak torque during various operating conditions such as motor starting, short circuit and motor bus transfer.

Motor B Transient Torques During Residual Voltage Transfer



g. 5. Transient peak-to-peak torque.

Test Results - Transient Currents & Torques during Residual Voltage MBT

Residual voltage transfer vs. Motor start and in-phase transfer (gray>normal start)

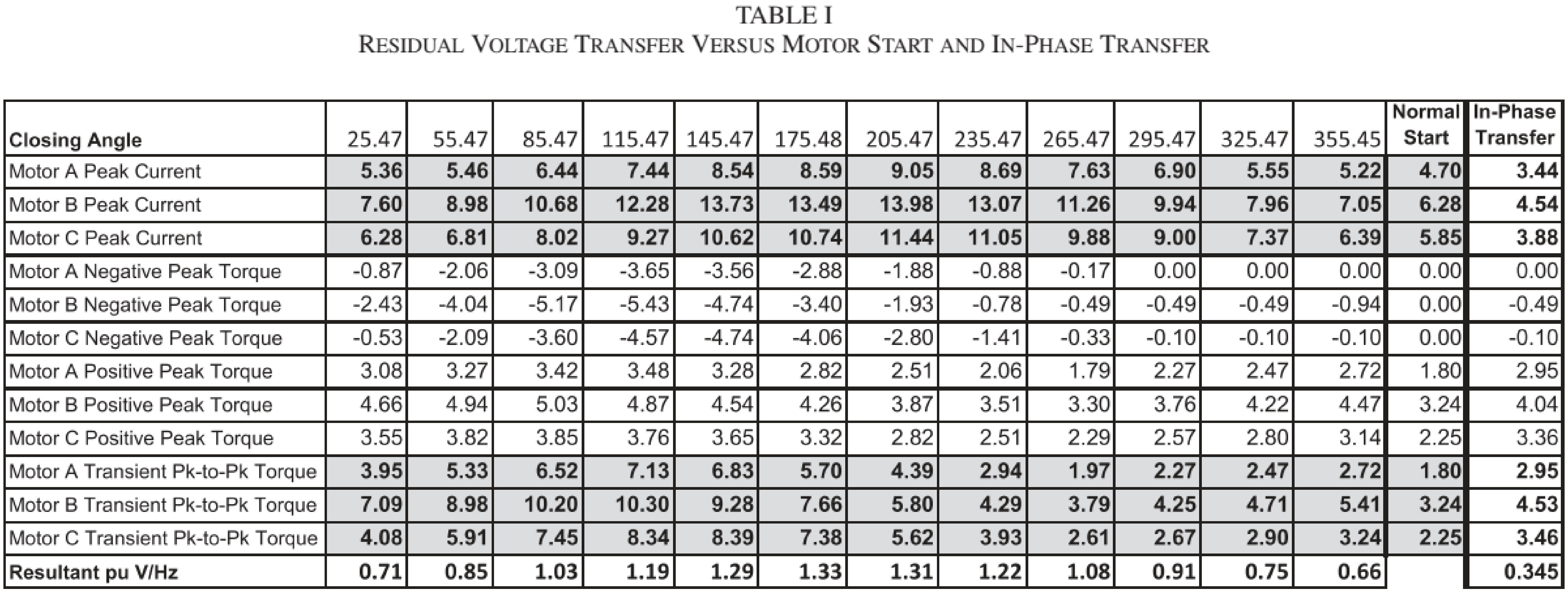


TABLE I
RESIDUAL VOLTAGE TRANSFER VERSUS MOTOR START AND IN-PHASE TRANSFER

Closing Angle	25.47	55.47	85.47	115.47	145.47	175.48	205.47	235.47	265.47	295.47	325.47	355.45	**Normal Start**	**In-Phase Transfer**
Motor A Peak Current	**5.36**	**5.46**	**6.44**	**7.44**	**8.54**	**8.59**	**9.05**	**8.69**	**7.63**	**6.90**	**5.55**	**5.22**	**4.70**	**3.44**
Motor B Peak Current	**7.60**	**8.98**	**10.68**	**12.28**	**13.73**	**13.49**	**13.98**	**13.07**	**11.26**	**9.94**	**7.96**	**7.05**	**6.28**	**4.54**
Motor C Peak Current	**6.28**	**6.81**	**8.02**	**9.27**	**10.62**	**10.74**	**11.44**	**11.05**	**9.88**	**9.00**	**7.37**	**6.39**	**5.85**	**3.88**
Motor A Negative Peak Torque	-0.87	-2.06	-3.09	-3.65	-3.56	-2.88	-1.88	-0.88	-0.17	0.00	0.00	0.00	0.00	0.00
Motor B Negative Peak Torque	-2.43	-4.04	-5.17	-5.43	-4.74	-3.40	-1.93	-0.78	-0.49	-0.49	-0.49	-0.94	0.00	-0.49
Motor C Negative Peak Torque	-0.53	-2.09	-3.60	-4.57	-4.74	-4.06	-2.80	-1.41	-0.33	-0.10	-0.10	-0.10	0.00	-0.10
Motor A Positive Peak Torque	3.08	3.27	3.42	3.48	3.28	2.82	2.51	2.06	1.79	2.27	2.47	2.72	1.80	2.95
Motor B Positive Peak Torque	4.66	4.94	5.03	4.87	4.54	4.26	3.87	3.51	3.30	3.76	4.22	4.47	3.24	4.04
Motor C Positive Peak Torque	3.55	3.82	3.85	3.76	3.65	3.32	2.82	2.51	2.29	2.57	2.80	3.14	2.25	3.36
Motor A Transient Pk-to-Pk Torque	**3.95**	**5.33**	**6.52**	**7.13**	**6.83**	**5.70**	**4.39**	**2.94**	**1.97**	**2.27**	**2.47**	**2.72**	**1.80**	**2.95**
Motor B Transient Pk-to-Pk Torque	**7.09**	**8.98**	**10.20**	**10.30**	**9.28**	**7.66**	**5.80**	**4.29**	**3.79**	**4.25**	**4.71**	**5.41**	**3.24**	**4.53**
Motor C Transient Pk-to-Pk Torque	**4.08**	**5.91**	**7.45**	**8.34**	**8.39**	**7.38**	**5.62**	**3.93**	**2.61**	**2.67**	**2.90**	**3.24**	**2.25**	**3.46**
Resultant pu V/Hz	**0.71**	**0.85**	**1.03**	**1.19**	**1.29**	**1.33**	**1.31**	**1.22**	**1.08**	**0.91**	**0.75**	**0.66**		**0.345**

Comparison of Currents and Torques Residual Voltage Transfer vs. Motor Start

- In all of the cases, the peak currents and peak-to-peak torques observed during residual voltage transfer on all motors are greater than the motor start currents and torques respectively.

- In particular, in the majority of cases, the currents during transfer are well in excess of six times rated current, which is generally specified for across-the-line motor starting.

Comparison of Currents and Torques Residual Voltage Transfer vs. In-Phase Transfer

- The In-Phase Transfer takes more than 27 cycles which is much more than the 10-cycle fast transfer limit specified by ANSI C50.41.
- The bus voltage at the point of In-Phase Transfer is 62% compared to <30% for a Residual Voltage Transfer.
- For all motors, in 67% of the tests, the peak-to-peak torques for In-Phase Transfers are much less than the peak-to-peak torques for Residual Voltage Transfers at larger angles.
- The frequency of the bus during the in-phase transfer reached 56.818 Hz and the corresponding pu V/Hz is 0.345 compared to the worst-case residual voltage transfer where the frequency is 53 Hz and the corresponding V/Hz is 1.33 pu.
- The peak-to-peak torque in the case of in-phase transfer is less than one-half of the peakto-peak torque during worst-case residual voltage transfer for all three motors (A, B, and C) simulated.
- The peak currents during in-phase transfer are lower than the motor start currents and, in all cases, lower than residual voltage transfer.

Test Results - Transient Currents & Torques During Residual Voltage MBT Vs Short Circuit

Residual voltage transfer vs. Motor 3-ø short circuit (gray>short circuit)

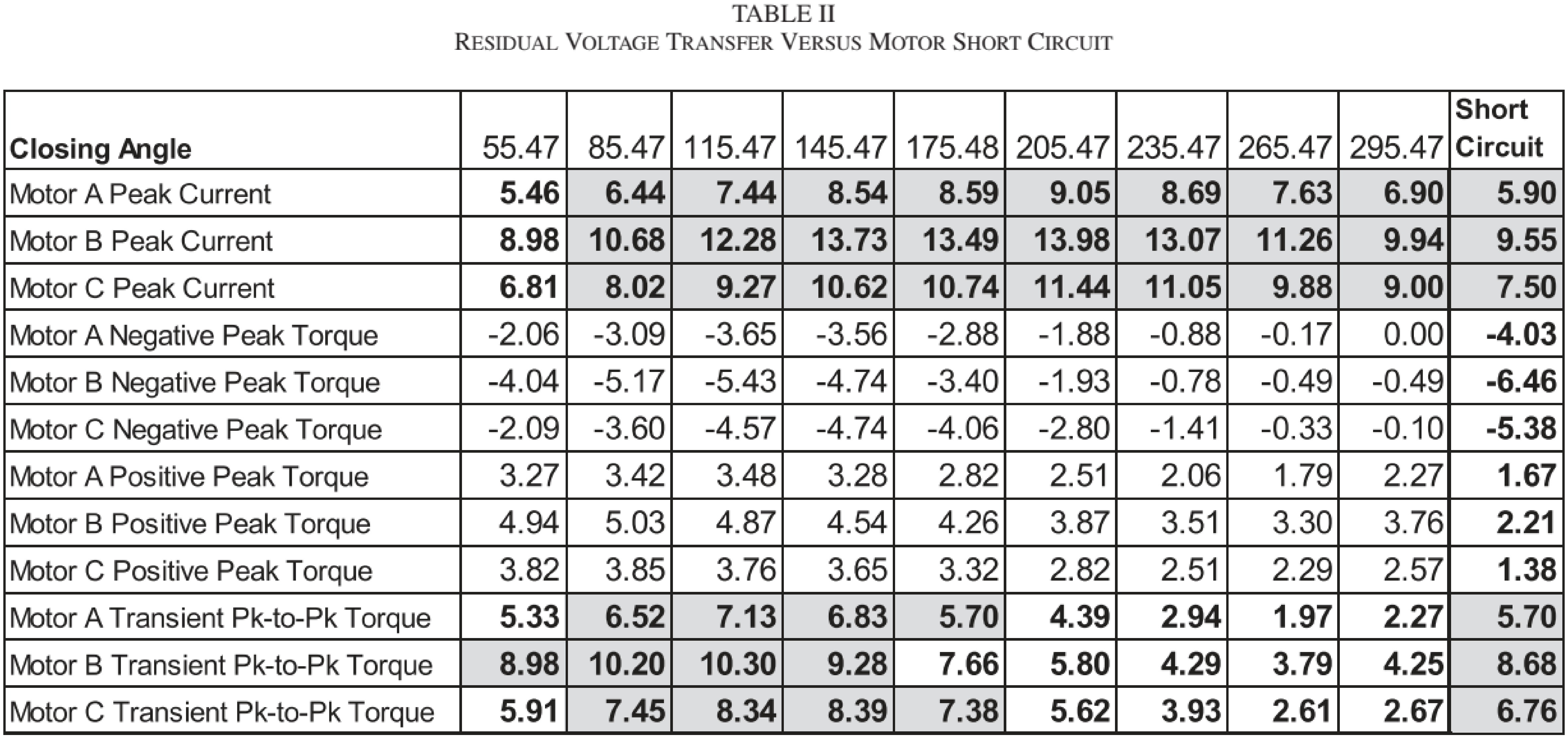


TABLE II
RESIDUAL VOLTAGE TRANSFER VERSUS MOTOR SHORT CIRCUIT

Closing Angle	55.47	85.47	115.47	145.47	175.48	205.47	235.47	265.47	295.47	**Short Circuit**
Motor A Peak Current	**5.46**	**6.44**	**7.44**	**8.54**	**8.59**	**9.05**	**8.69**	**7.63**	**6.90**	**5.90**
Motor B Peak Current	**8.98**	**10.68**	**12.28**	**13.73**	**13.49**	**13.98**	**13.07**	**11.26**	**9.94**	**9.55**
Motor C Peak Current	**6.81**	**8.02**	**9.27**	**10.62**	**10.74**	**11.44**	**11.05**	**9.88**	**9.00**	**7.50**
Motor A Negative Peak Torque	-2.06	-3.09	-3.65	-3.56	-2.88	-1.88	-0.88	-0.17	0.00	**-4.03**
Motor B Negative Peak Torque	-4.04	-5.17	-5.43	-4.74	-3.40	-1.93	-0.78	-0.49	-0.49	**-6.46**
Motor C Negative Peak Torque	-2.09	-3.60	-4.57	-4.74	-4.06	-2.80	-1.41	-0.33	-0.10	**-5.38**
Motor A Positive Peak Torque	3.27	3.42	3.48	3.28	2.82	2.51	2.06	1.79	2.27	**1.67**
Motor B Positive Peak Torque	4.94	5.03	4.87	4.54	4.26	3.87	3.51	3.30	3.76	**2.21**
Motor C Positive Peak Torque	3.82	3.85	3.76	3.65	3.32	2.82	2.51	2.29	2.57	**1.38**
Motor A Transient Pk-to-Pk Torque	**5.33**	**6.52**	**7.13**	**6.83**	**5.70**	**4.39**	**2.94**	**1.97**	**2.27**	**5.70**
Motor B Transient Pk-to-Pk Torque	**8.98**	**10.20**	**10.30**	**9.28**	**7.66**	**5.80**	**4.29**	**3.79**	**4.25**	**8.68**
Motor C Transient Pk-to-Pk Torque	**5.91**	**7.45**	**8.34**	**8.39**	**7.38**	**5.62**	**3.93**	**2.61**	**2.67**	**6.76**

Comparison of Currents and Torques -- Residual Voltage Transfer vs Motor Short Circuit

- For example, the worst-case peak-to-peak torque during residual voltage transfer for Motor A is 7.13 pu versus a SCT of 5.70 pu, for Motor B is 10.30 pu versus a SCT of 8.68 and for Motor C is 8.39 versus an SCT of 6.76.
- As the nature of these torques is cyclic or pulsating, this could generate high mechanical vibration resulting in possible cumulative damage to the motors and any mechanical equipment connected to them.
- The peak current in motors during Residual Voltage Transfers is higher than the Three-Phase Short Circuit Currents in more than 67% of the cases.
- High currents passing through the motor conductors cause high mechanical stresses on the conductors, fixed in stator slots by wedges, and held in end windings by a combination of epoxy, blocking and lashings. This mechanical stress can result in damage to the insulation surrounding the stator conductors and, over time, it can cause a short circuit in the stator windings.

Transient Currents During Residual Voltage Transfer Compared

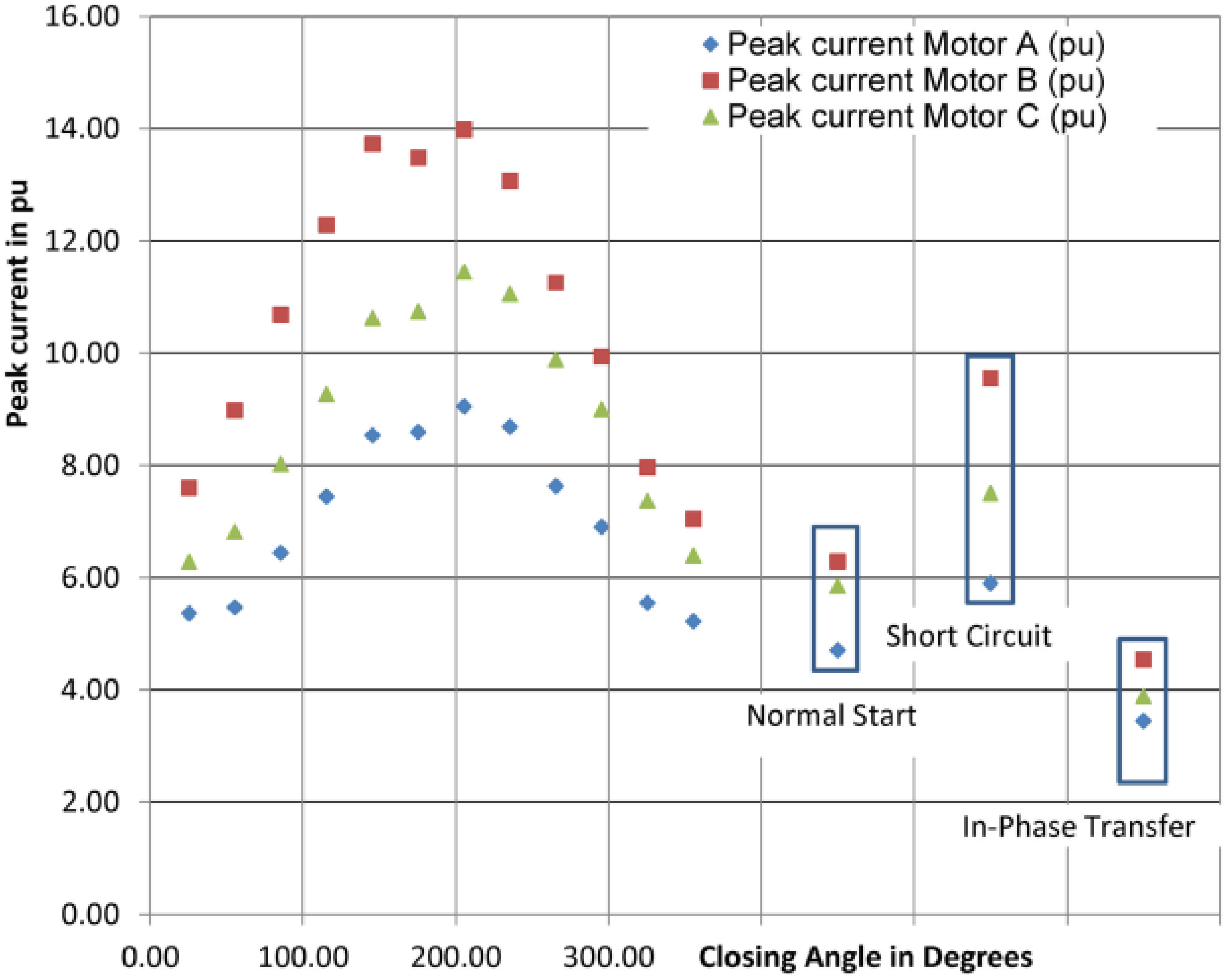
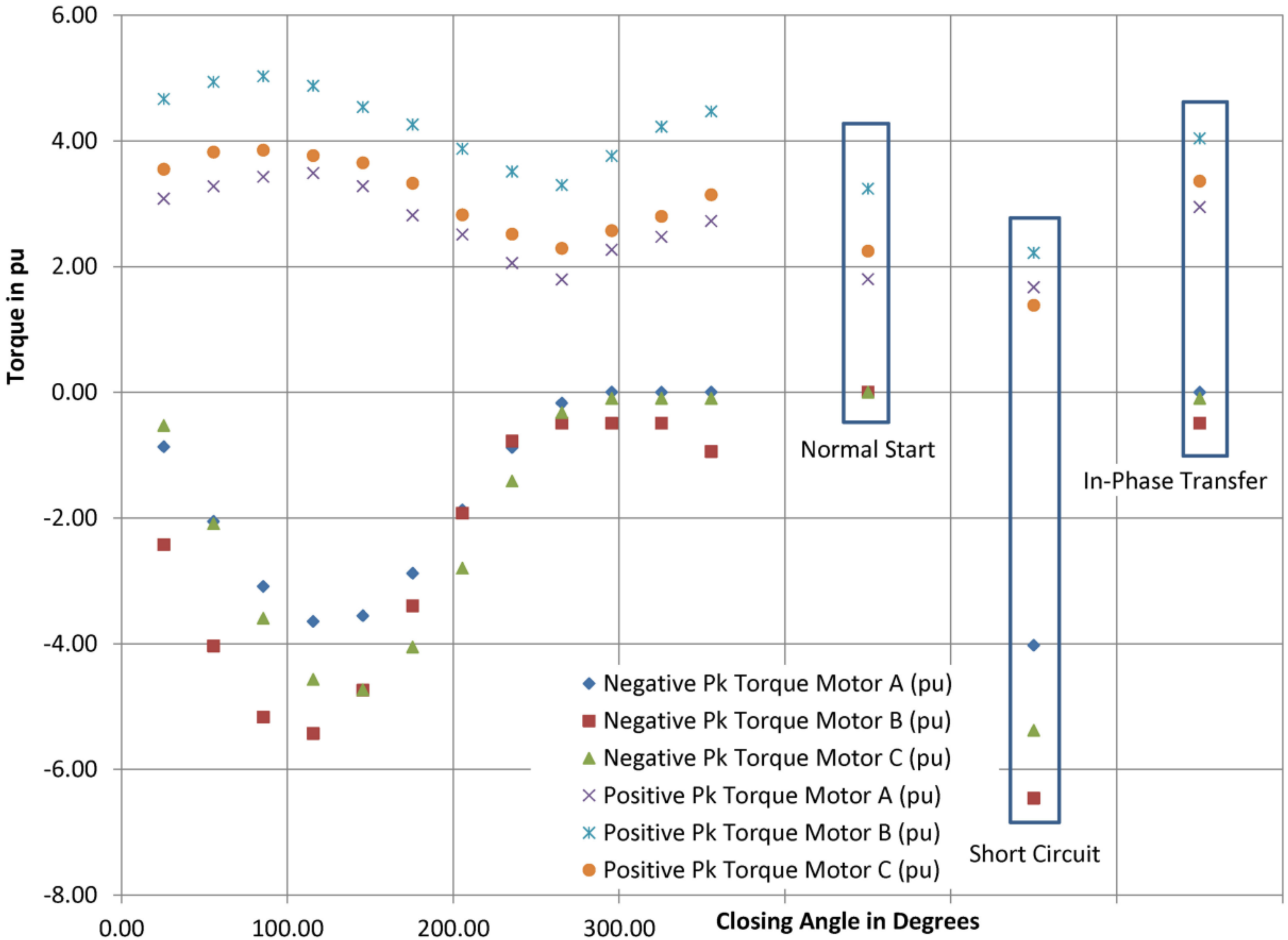


Fig. 9. Graph of peak current versus closing angle.

Transient Torques During Residual Voltage Transfer Compared



11. Graph of positive and negative peak transient torque versus closing angle.

Transient Pk to Pk Torques During Residual Voltage Transfer Compared

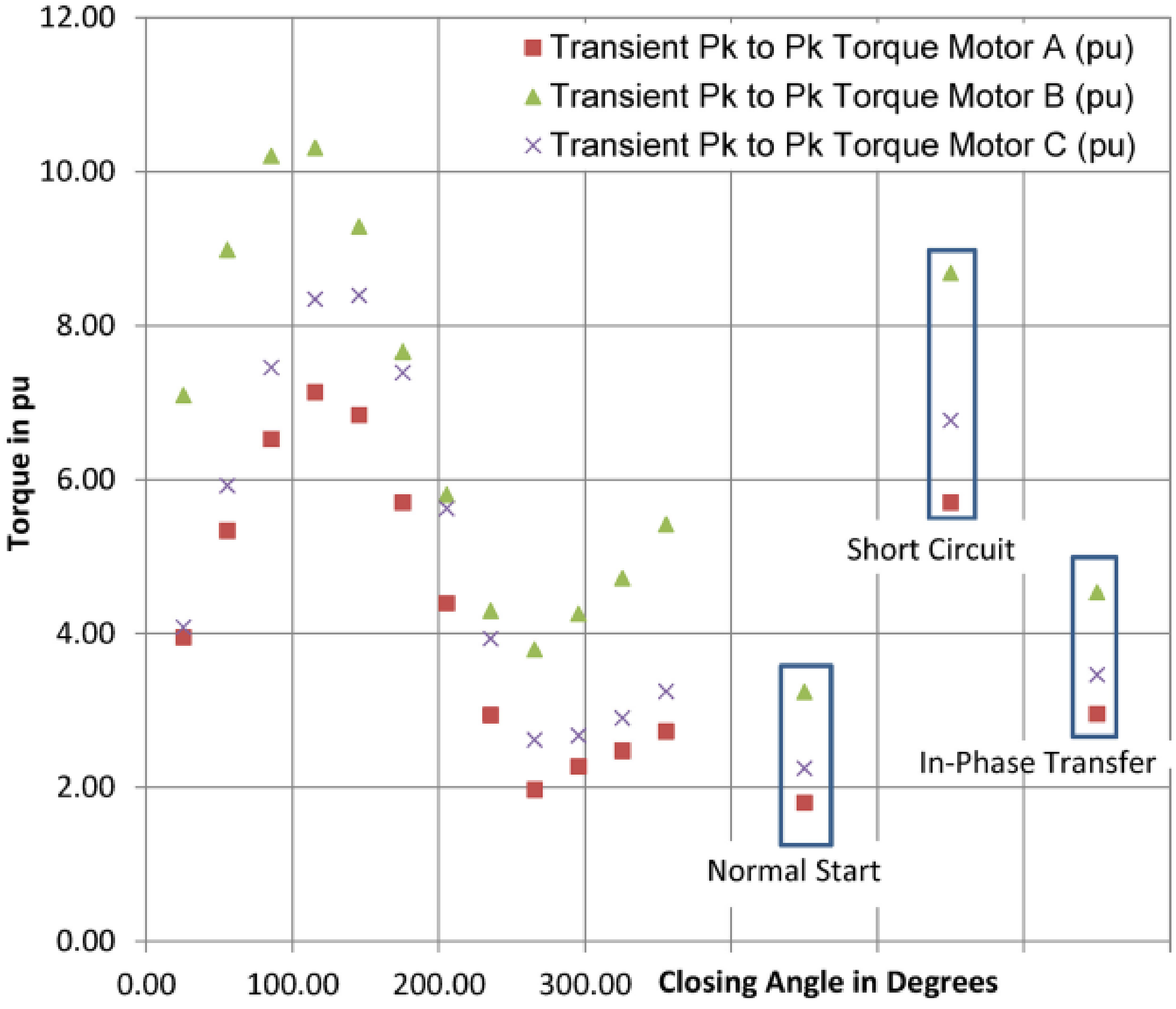
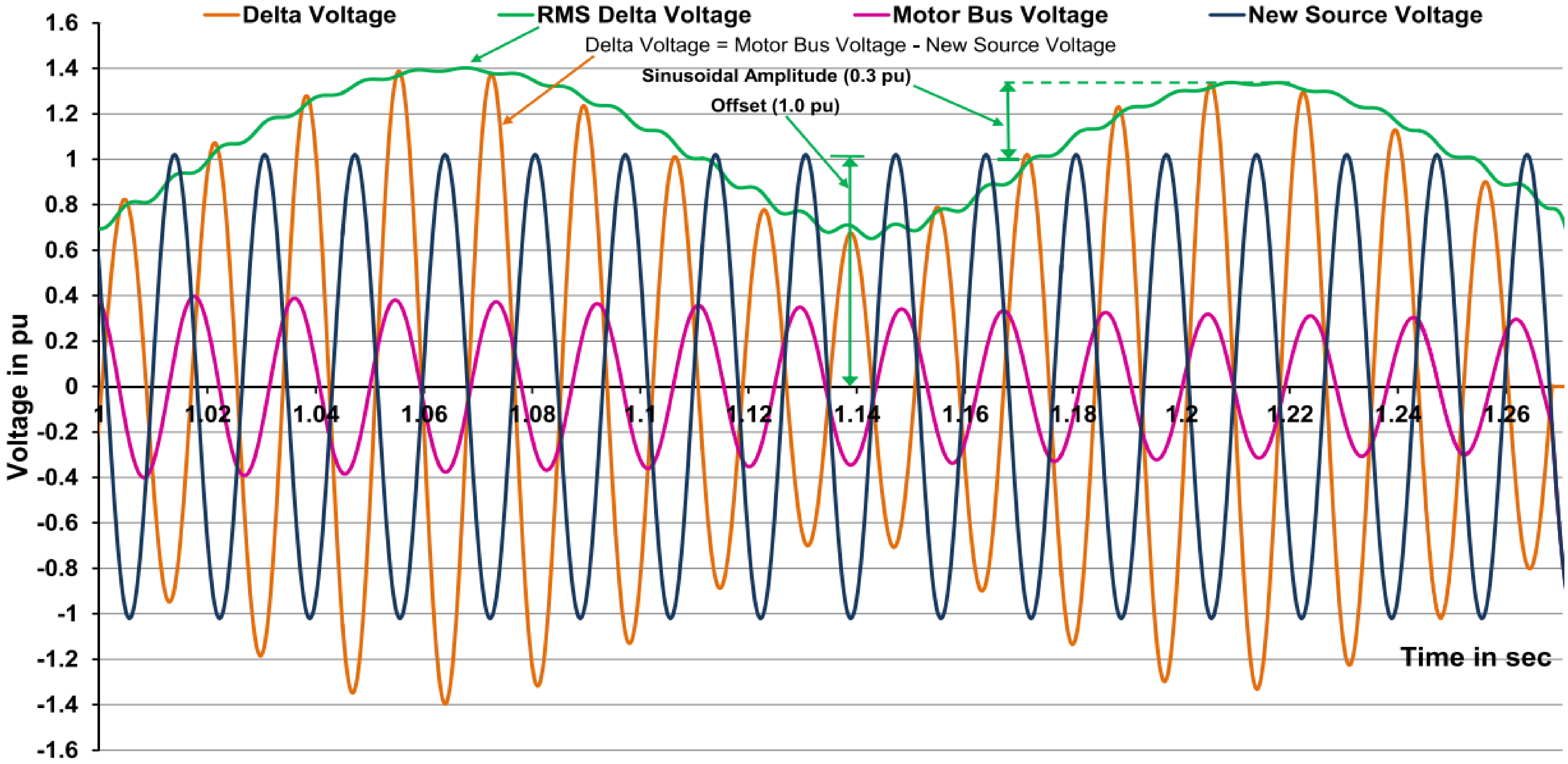


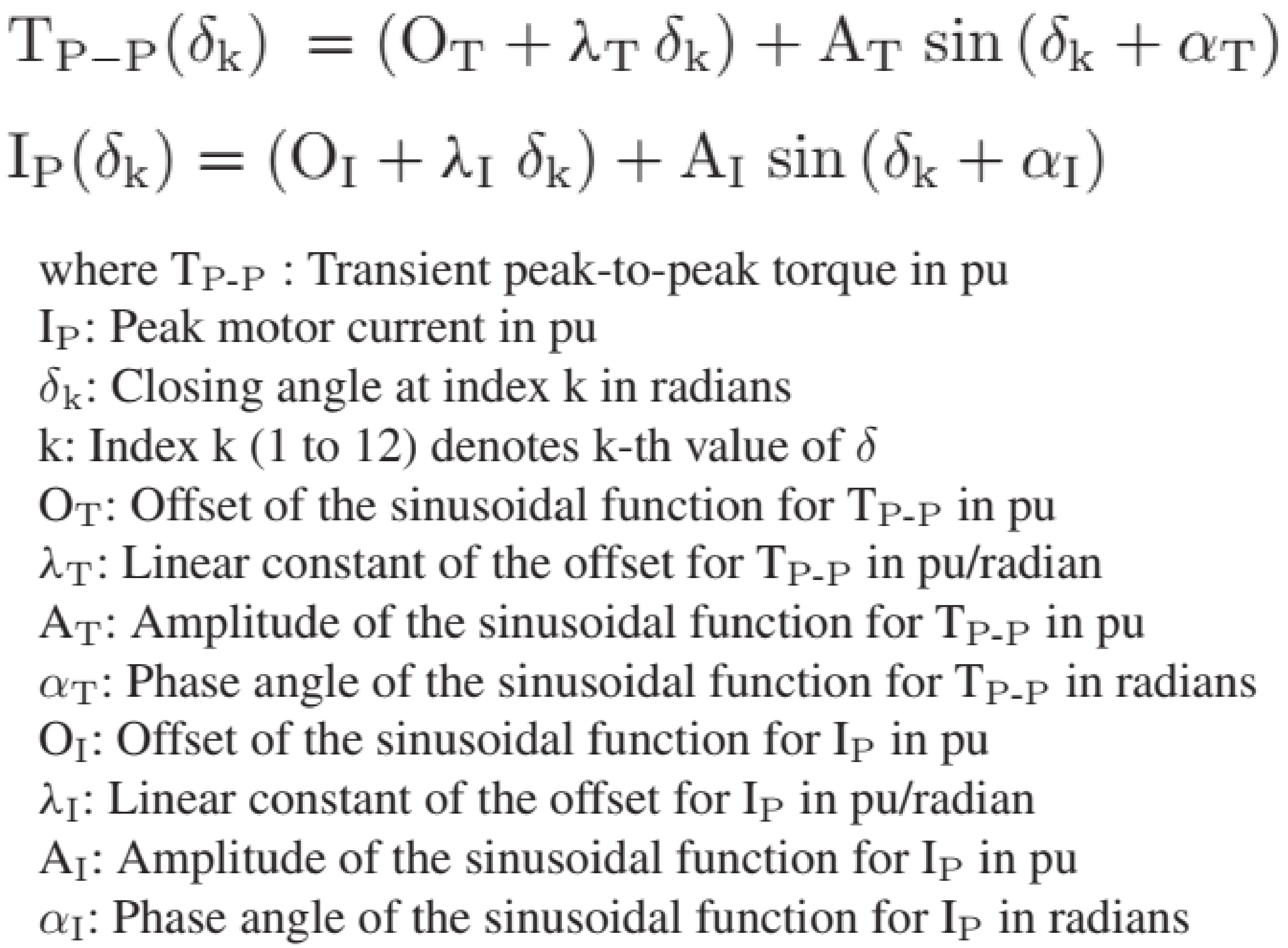
Fig. 10. Graph of transient peak-to-peak torque versus closing angle.

Delta Voltage vs Time



. 12. Graph of instantaneous, RMS, and square of RMS value of delta voltage.

Least Squares curve-fit of Pk-Pk transient torque and Peak current

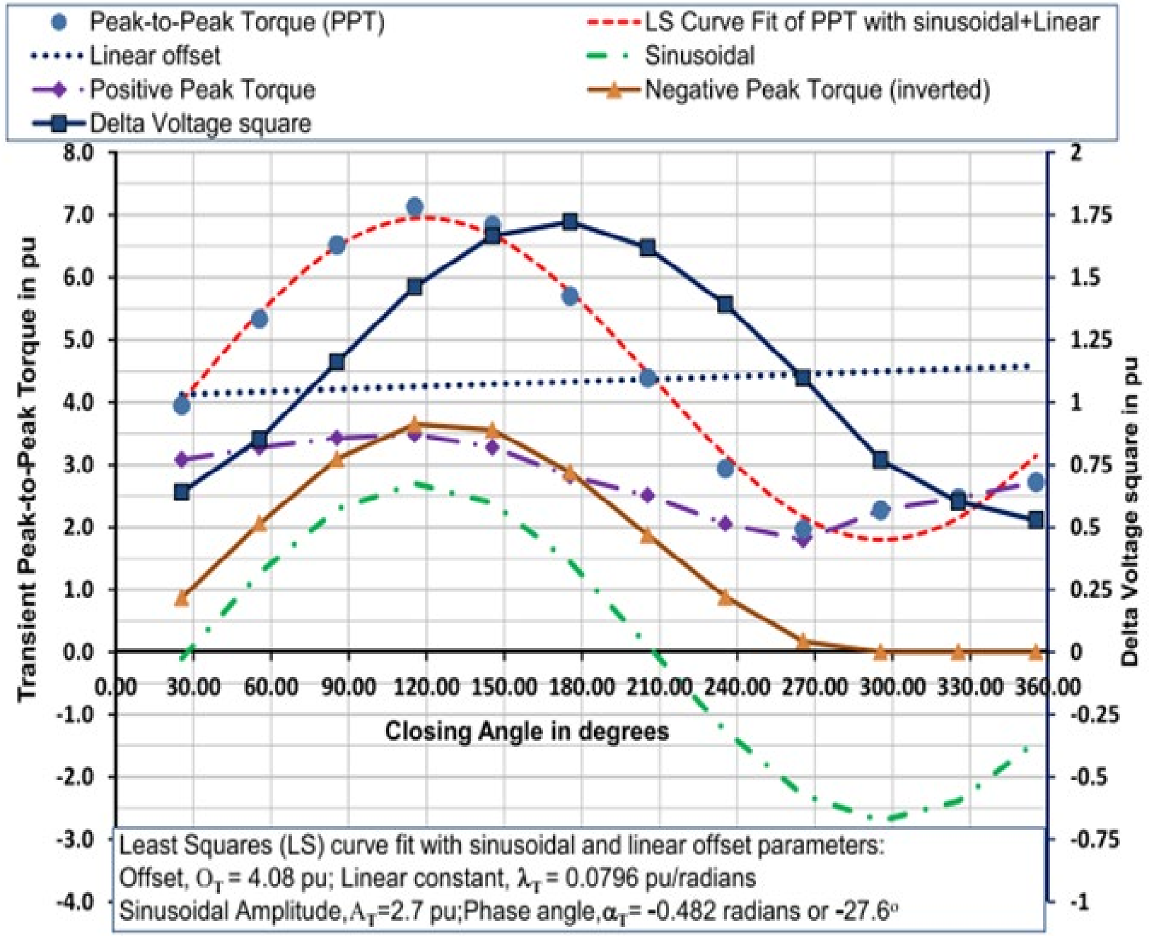


$$T_{P-P}(\delta_k) = (O_T + \lambda_T\,\delta_k) + A_T \sin(\delta_k + \alpha_T)$$

$$I_P(\delta_k) = (O_I + \lambda_I\,\delta_k) + A_I \sin(\delta_k + \alpha_I)$$

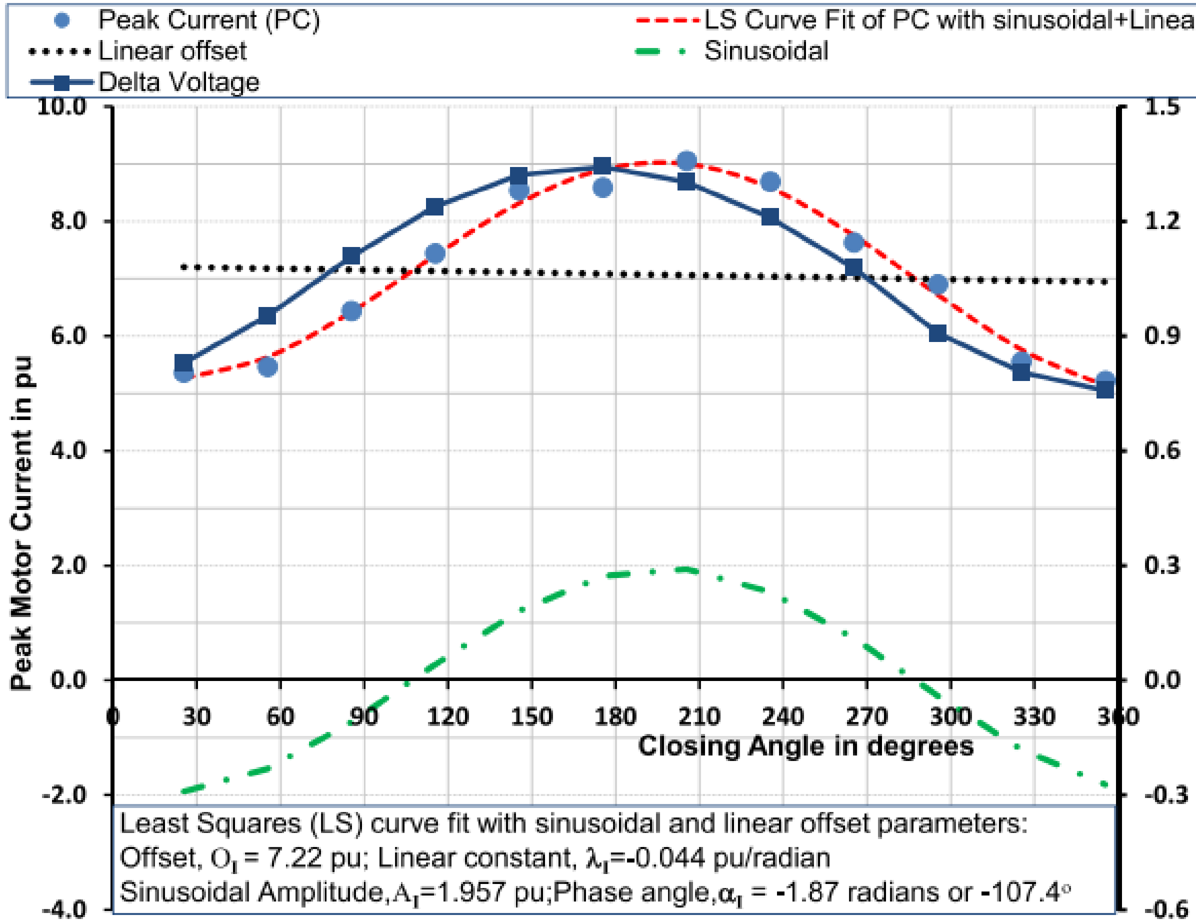
where $T_{P\text{-}P}$: Transient peak-to-peak torque in pu
I_P: Peak motor current in pu
δ_k: Closing angle at index k in radians
k: Index k (1 to 12) denotes k-th value of δ
O_T: Offset of the sinusoidal function for $T_{P\text{-}P}$ in pu
λ_T: Linear constant of the offset for $T_{P\text{-}P}$ in pu/radian
A_T: Amplitude of the sinusoidal function for $T_{P\text{-}P}$ in pu
α_T: Phase angle of the sinusoidal function for $T_{P\text{-}P}$ in radians
O_I: Offset of the sinusoidal function for I_P in pu
λ_I: Linear constant of the offset for I_P in pu/radian
A_I: Amplitude of the sinusoidal function for I_P in pu
α_I: Phase angle of the sinusoidal function for I_P in radians

Pk-Pk Torque and Peak Current vs Closing Angle for Motor A



Least Squares (LS) curve fit with sinusoidal and linear offset parameters:
Offset, O_T = 4.08 pu; Linear constant, λ_T = 0.0796 pu/radians
Sinusoidal Amplitude,A_T=2.7 pu;Phase angle,α_T= -0.482 radians or -27.6°

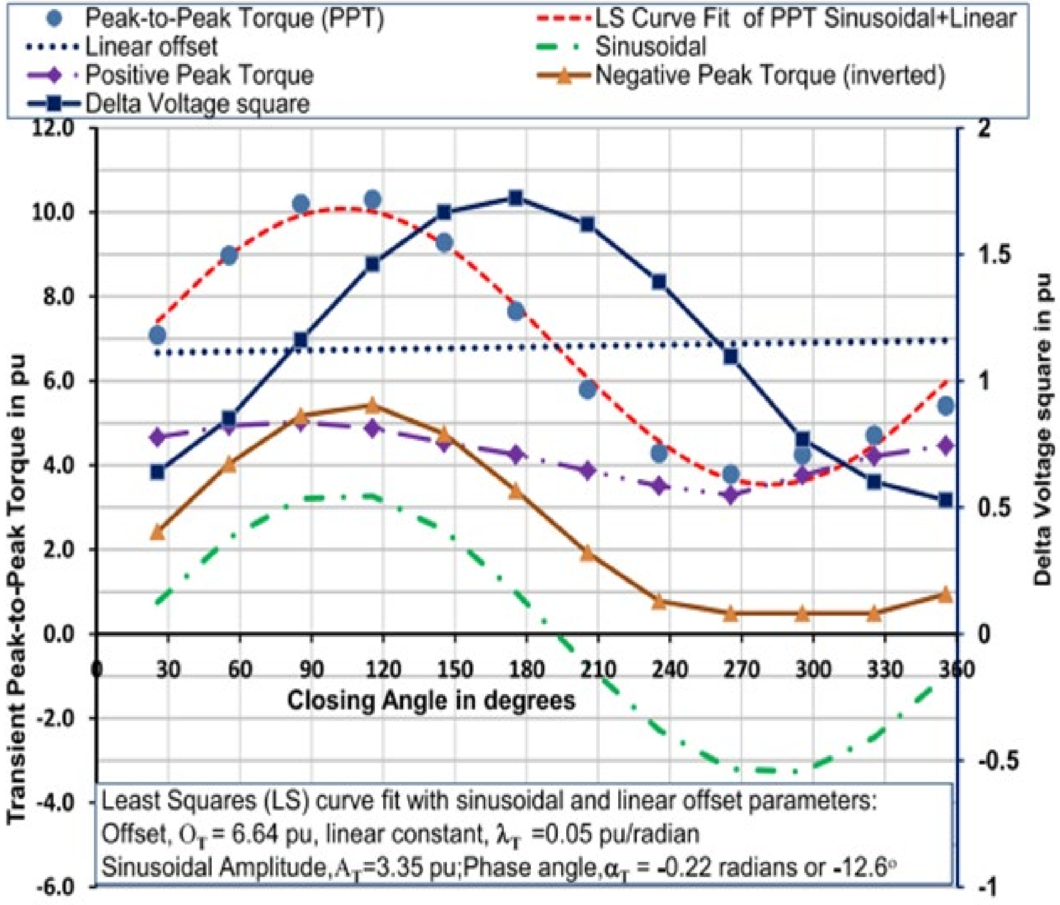
Fig. 13. Graph of Motor A transient peak-to-peak torque versus closing angle.



Least Squares (LS) curve fit with sinusoidal and linear offset parameters:
Offset, O_I = 7.22 pu; Linear constant, λ_I=-0.044 pu/radian
Sinusoidal Amplitude,A_I=1.957 pu;Phase angle,α_I = -1.87 radians or -107.4°

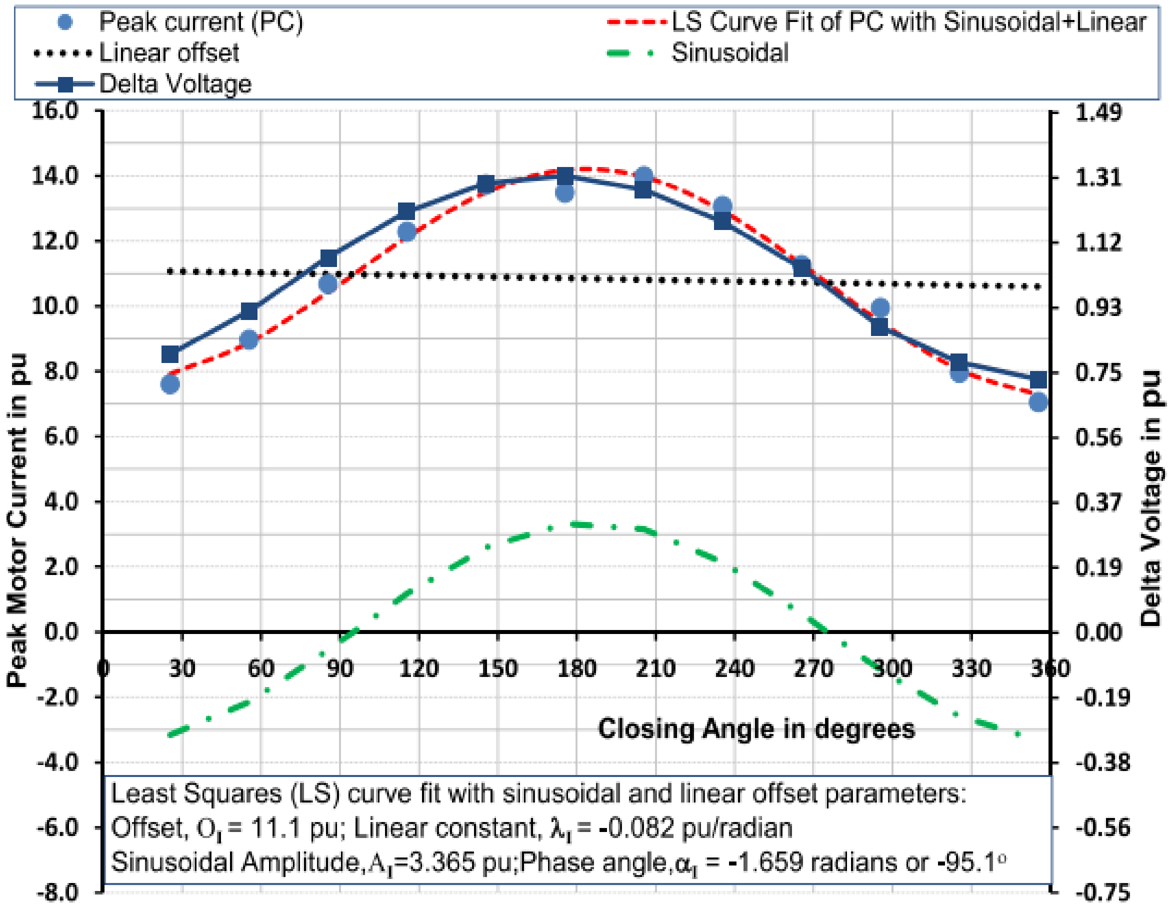
Fig. 16. Graph of Motor A peak current versus closing angle.

Pk-Pk Torque and Peak Current vs Closing Angle for Motor B



Least Squares (LS) curve fit with sinusoidal and linear offset parameters:
Offset, O_T = 6.64 pu, linear constant, λ_T =0.05 pu/radian
Sinusoidal Amplitude,A_T=3.35 pu;Phase angle,α_T = -0.22 radians or -12.6°

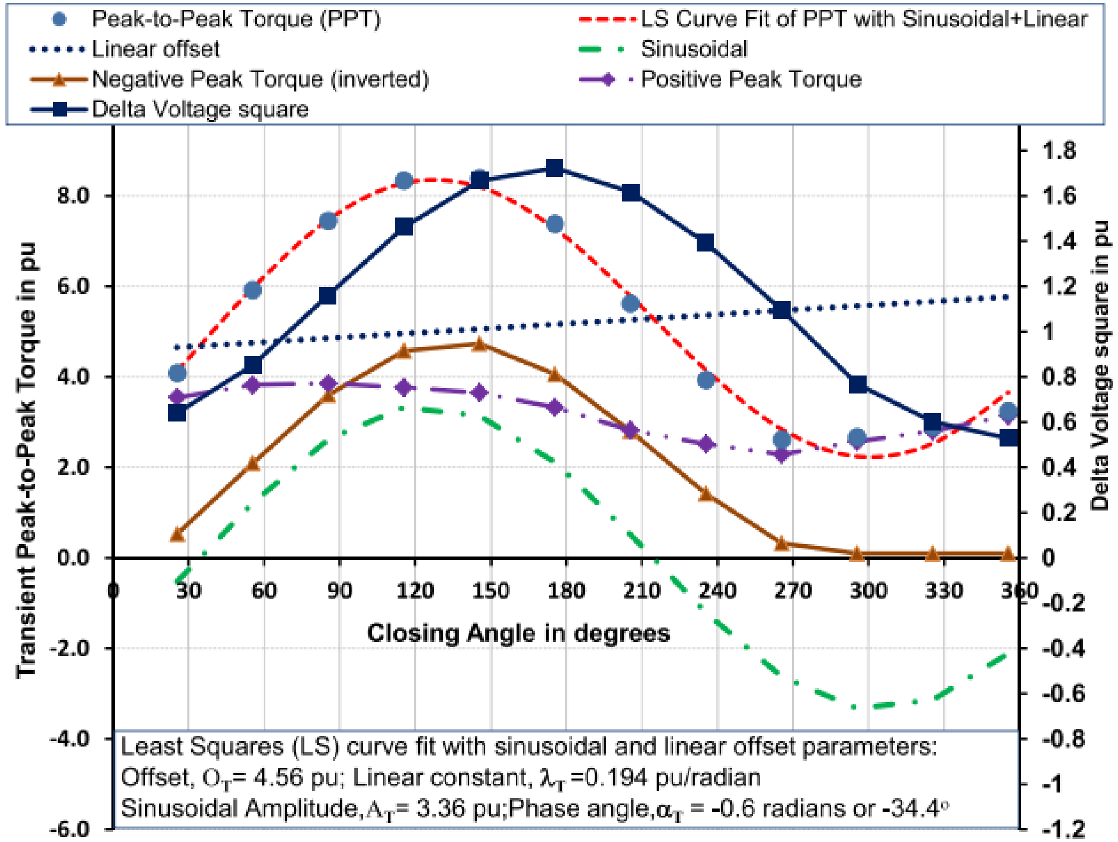
g. 14. Graph of Motor B transient peak-to-peak torque versus closing angle.



Least Squares (LS) curve fit with sinusoidal and linear offset parameters:
Offset, O_I = 11.1 pu; Linear constant, λ_I = -0.082 pu/radian
Sinusoidal Amplitude,A_I=3.365 pu;Phase angle,α_I = -1.659 radians or -95.1°

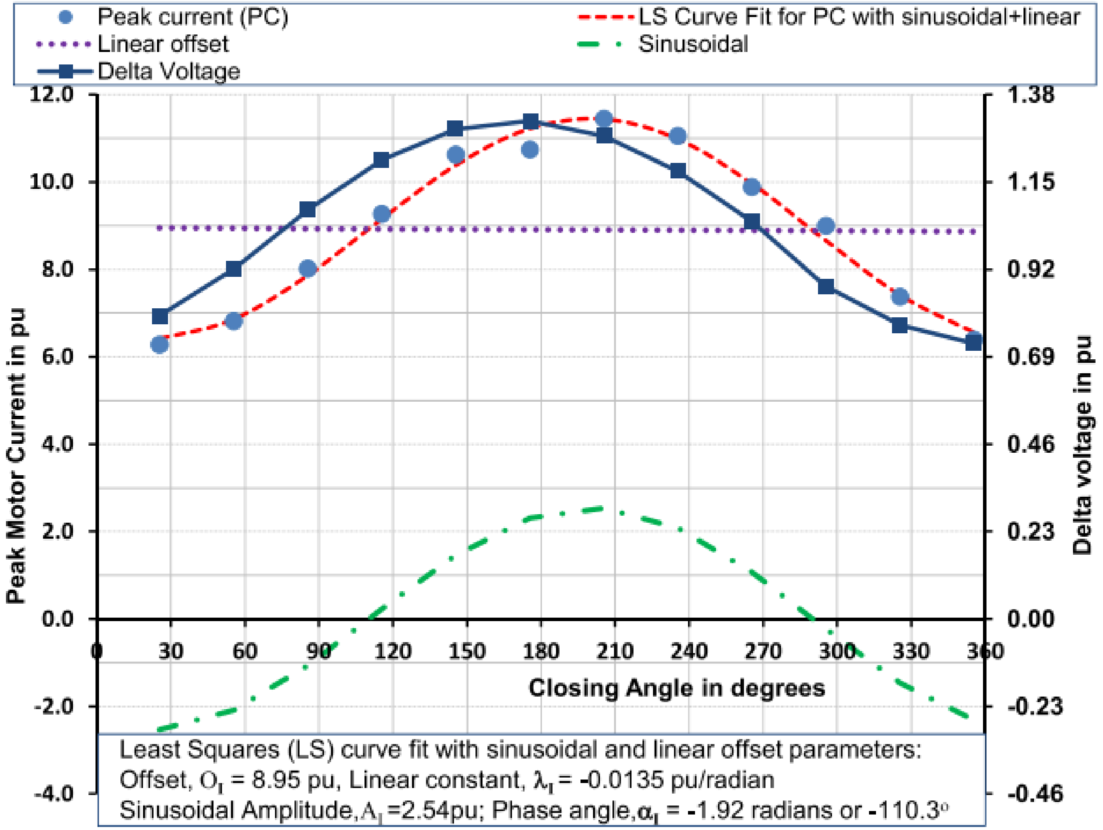
Fig. 17. Graph of Motor B peak current versus closing angle.

Pk-Pk Torque and Peak Current vs Closing Angle for Motor C



Least Squares (LS) curve fit with sinusoidal and linear offset parameters:
Offset, O_T= 4.56 pu; Linear constant, λ_T=0.194 pu/radian
Sinusoidal Amplitude,A_T= 3.36 pu;Phase angle,α_T = -0.6 radians or -34.4°

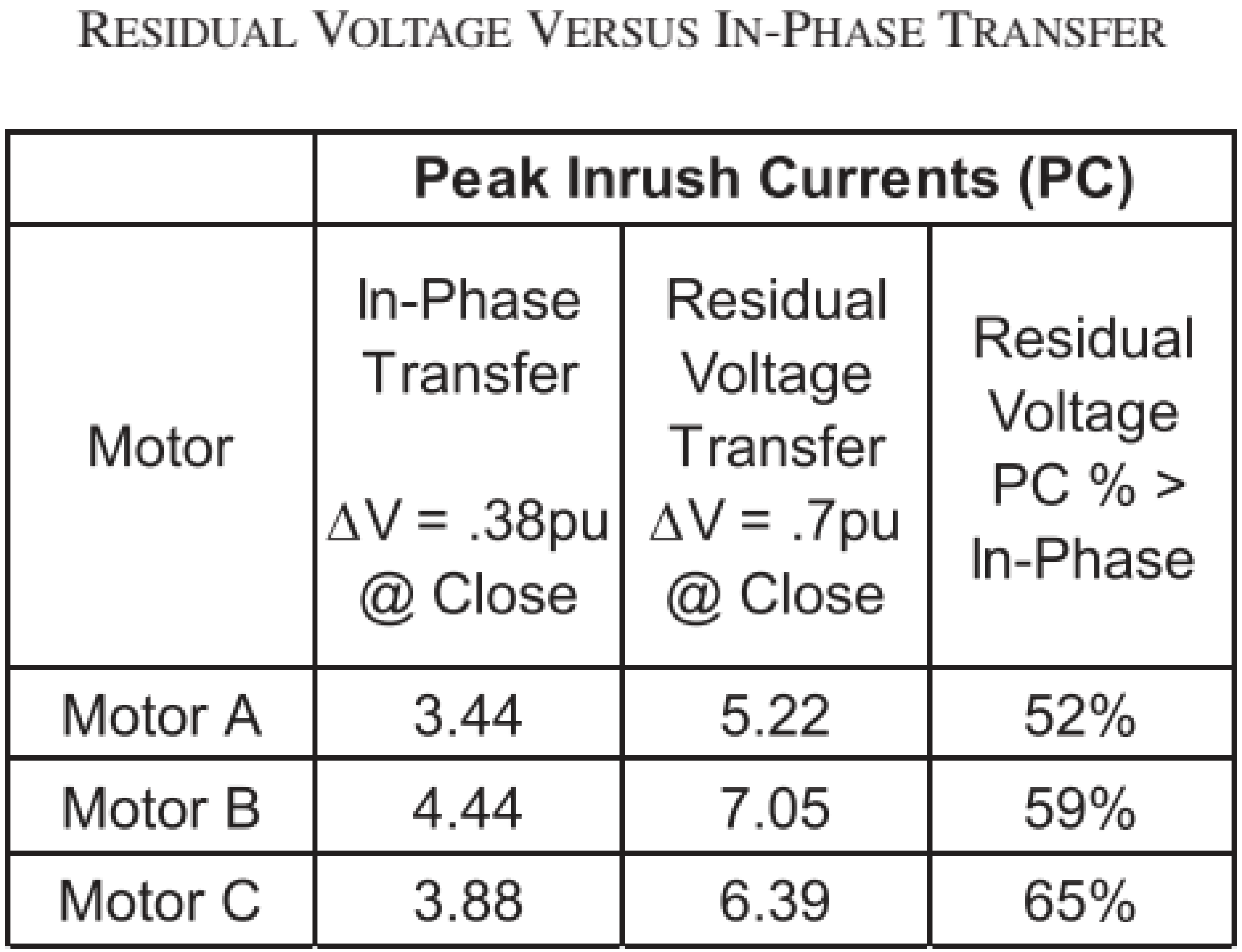
ig. 15. Graph of Motor C transient peak-to-peak torque versus closing angle.



Least Squares (LS) curve fit with sinusoidal and linear offset parameters:
Offset, O_I = 8.95 pu, Linear constant, λ_I = -0.0135 pu/radian
Sinusoidal Amplitude,A_I =2.54pu; Phase angle,α_I = -1.92 radians or -110.3°

Fig. 18. Graph of Motor C peak current versus closing angle.

Peak Inrush Currents for Each Motor



RESIDUAL VOLTAGE VERSUS IN-PHASE TRANSFER

	Peak Inrush Currents (PC)		
Motor	In-Phase Transfer ΔV = .38pu @ Close	Residual Voltage Transfer ΔV = .7pu @ Close	Residual Voltage PC % > In-Phase
Motor A	3.44	5.22	52%
Motor B	4.44	7.05	59%
Motor C	3.88	6.39	65%

Summary of Simulation Results

- There is a high correlation of Torque Ratio vs. Ø Angle at Close.
- Transfers that produce dangerously high Torques are given a passing grade by the 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 C50.41 Standard, then the industry must use a torque-based criterion to assess if transfers are being completed within acceptable torque limits.
- Residual Voltage Transfers, where the phase angle and slip frequency are ignored, can produce dangerously high torques due to significantly out-of-phase closures.
- These results demonstrate that the in-phase transfer method is far superior to even the best 0° phase angle close by the residual voltage transfer method, which has only a 1 in 360 chance of ever occurring.

Residual Voltage Transfer – additional discussion

High Currents:

- May cause thermal and mechanical damage to stator conductors and insulation.
- May cause tripping of motor instantaneous overcurrent protective relays.
- May cause tripping of feeder and transformer overcurrent protective relays.

High Torques

- Will result in cumulative loss-of-life, motor fatigue, and potential early life failure.
- Large cyclic torques (peak-to-peak) can cause mechanical vibration and damage to the bearings, shafts, couplings, gearboxes and loads. If the peak shaft stresses exceed the yield strength of the shaft material, then immediate cracks will occur.

Residual Voltage Transfer Test Conclusions

Significant Speed and Voltage Decay

- Load shed may be necessary if the new source cannot reaccelerate all the motors at once.
- The transfer could cause excessive plant voltage dip causing motor trip or dropout on other buses.

DISCUSSION

- Acknowledging these significant problems, some in the industry have elected only to perform dead transfers, waiting until the motors have stopped and then restarting the whole process. This strategy is extremely expensive and opens exposure to the risk of having to perform an unnecessary complete shutdown and restart of the process. There is no need to resort to such extreme measures since Synchronous Fast and In-Phase Transfers always occur at much higher voltages, at much lower slip frequencies, and coupled with the synchronous closure, provide a far gentler transfer than the “blind” Residual Voltage method. Safe transfers can be performed rapidly and seamlessly with no effect on process.

Questions?

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