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EUR19_02 - Motor Bus Transfer Tutorial

Thomas R. Beckwith
Beckwith Electric Company
Author
Mohamed Abdel Khalek Mohamed
Beckwith Electric Company
Presenter

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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

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IEEE Guide for AC Motor Protection

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IEEE Guide for AC Motor Protection

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IEEE Std C37.96™-2012
(Revision of
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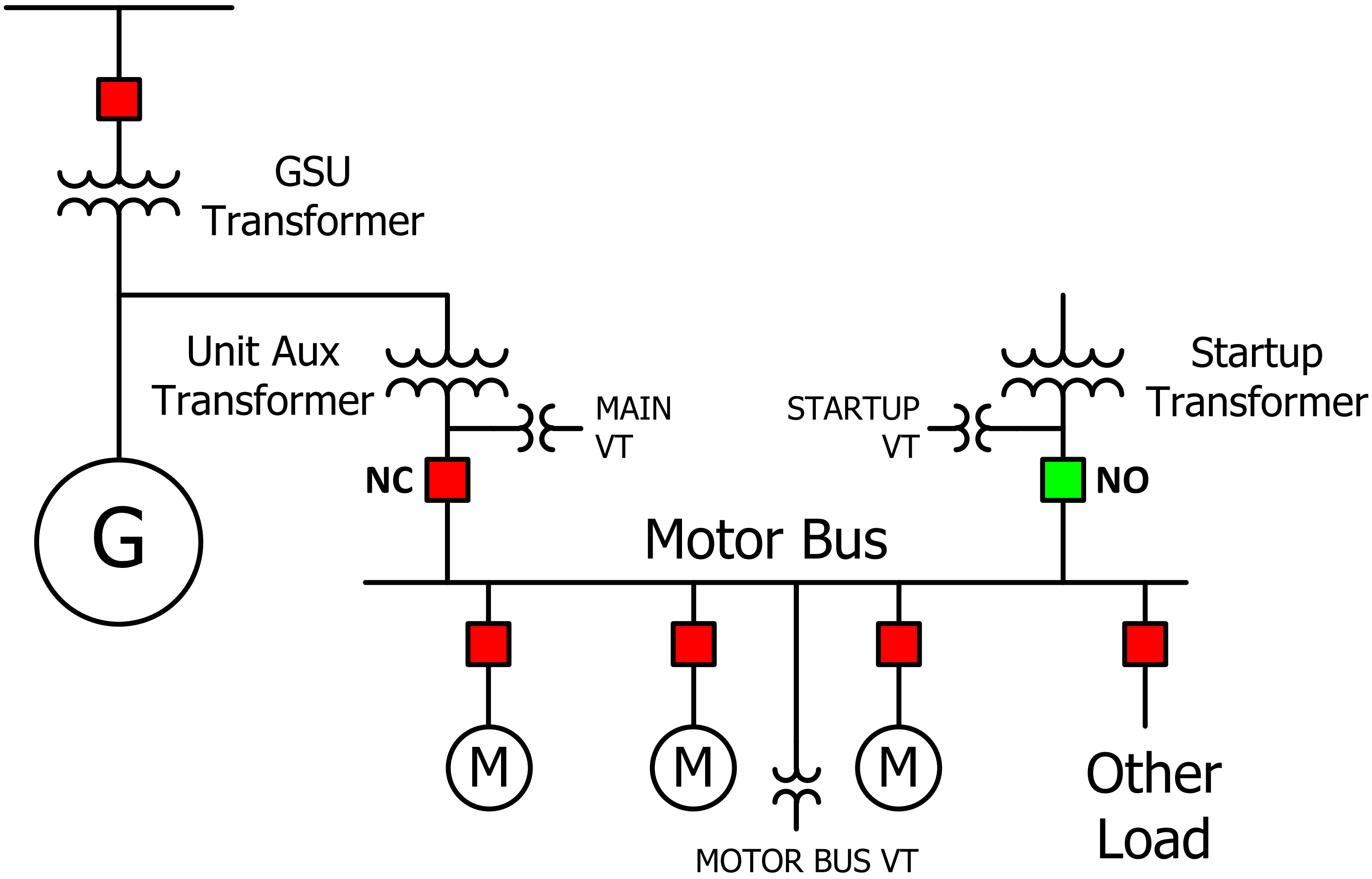
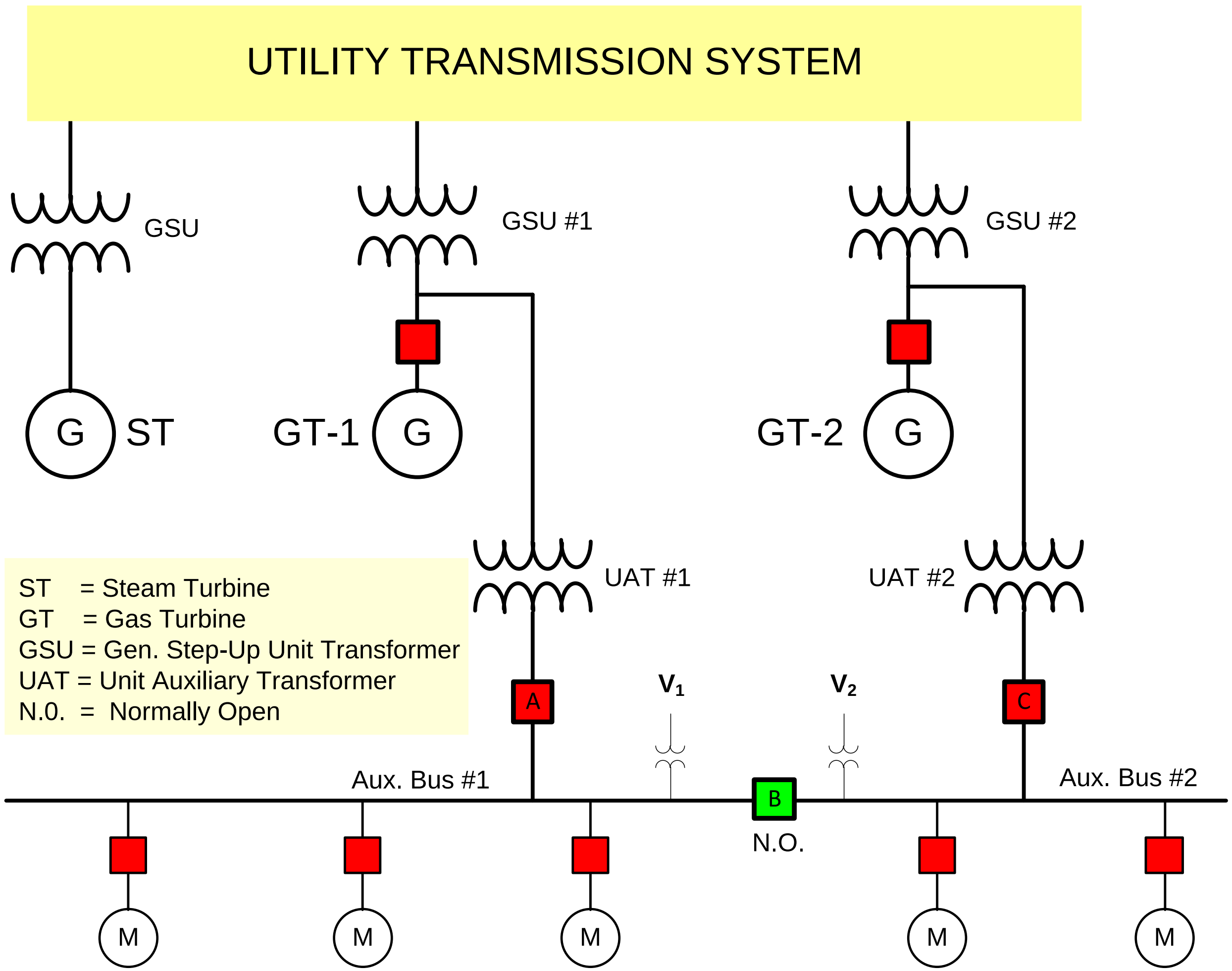
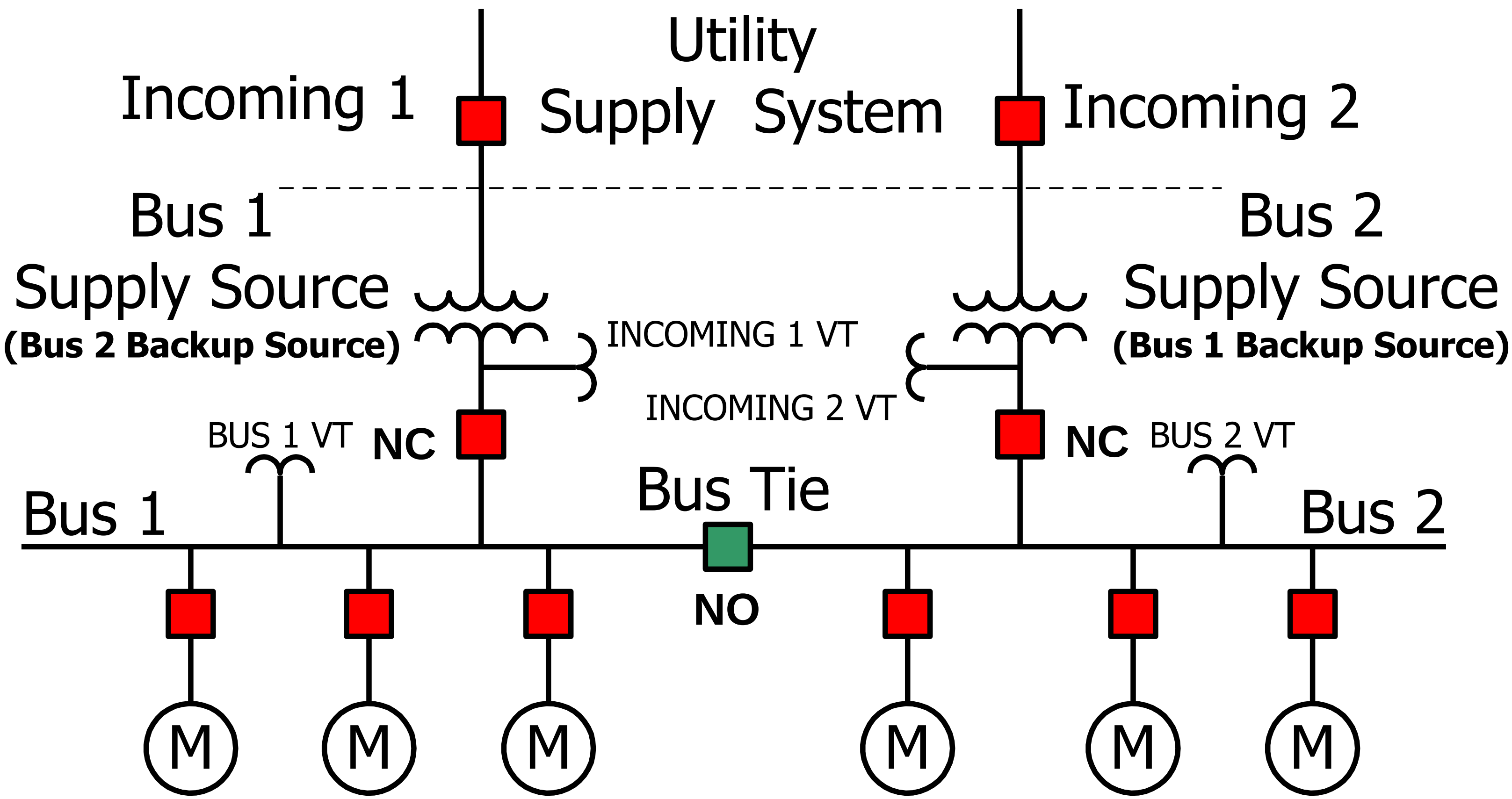
Unit-Connected Generator Motor Bus



Combined Cycle Plant Motor Bus



Typical Industrial Plant One-Line



Motor Bus Transfer Classification

- **Closed Transition**
  - Hot Parallel Transfer

- **Open Transition - Methods**

  - Fast Transfer
  - In-Phase Transfer
  - Residual Voltage Transfer
  - Fixed Time Transfer

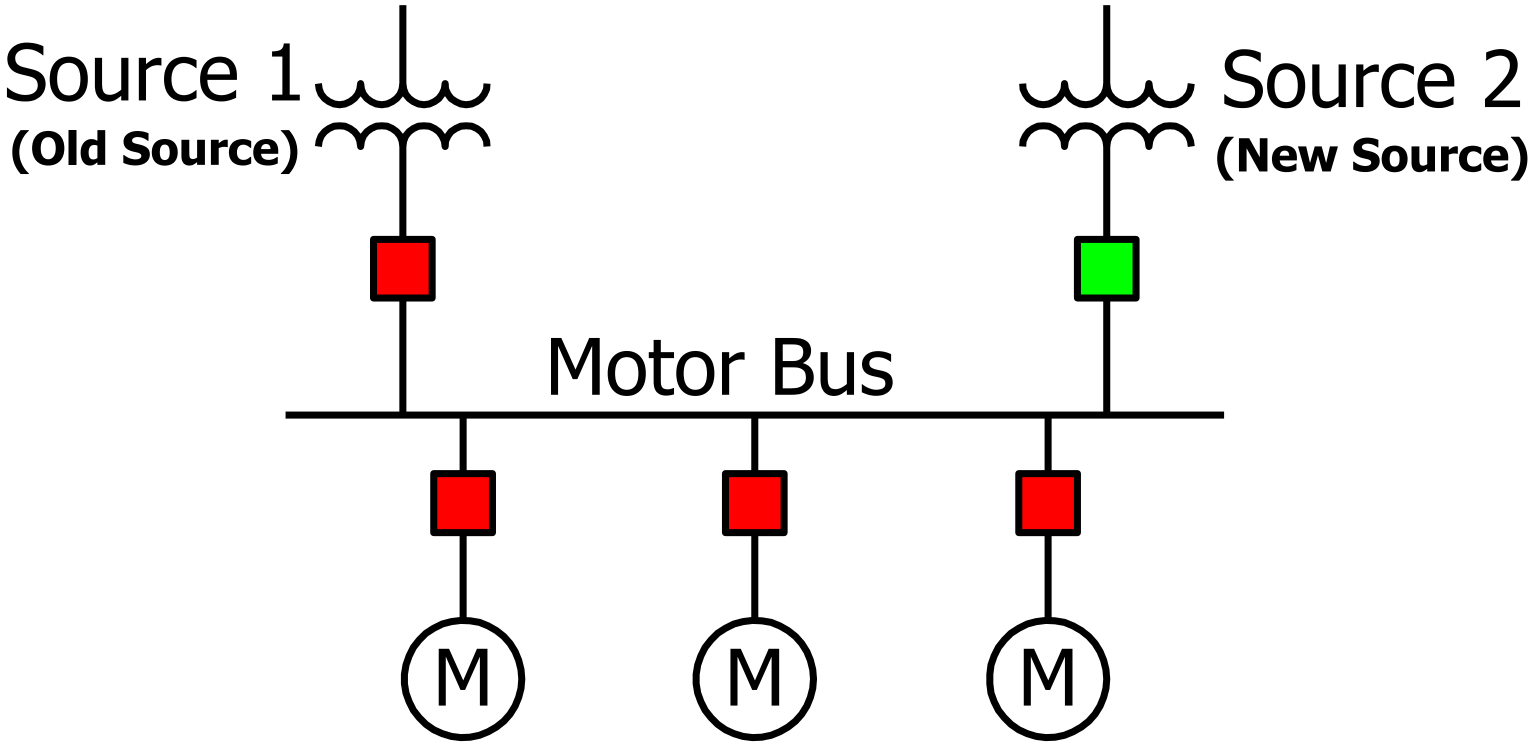
- **Open Transition - Modes**

  - Sequential
  - Simultaneous

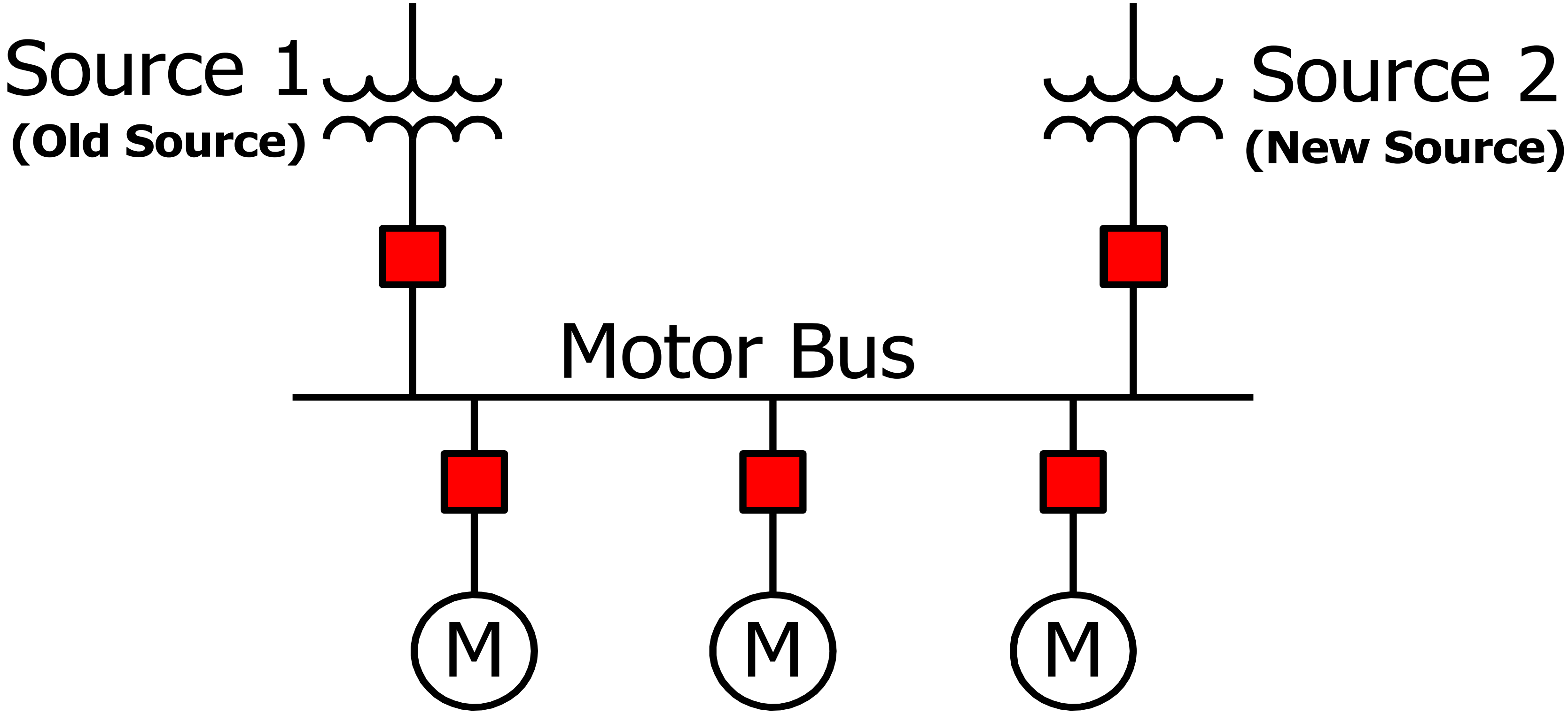
Closed Transition – Hot Parallel Transfer

- 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, but 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.

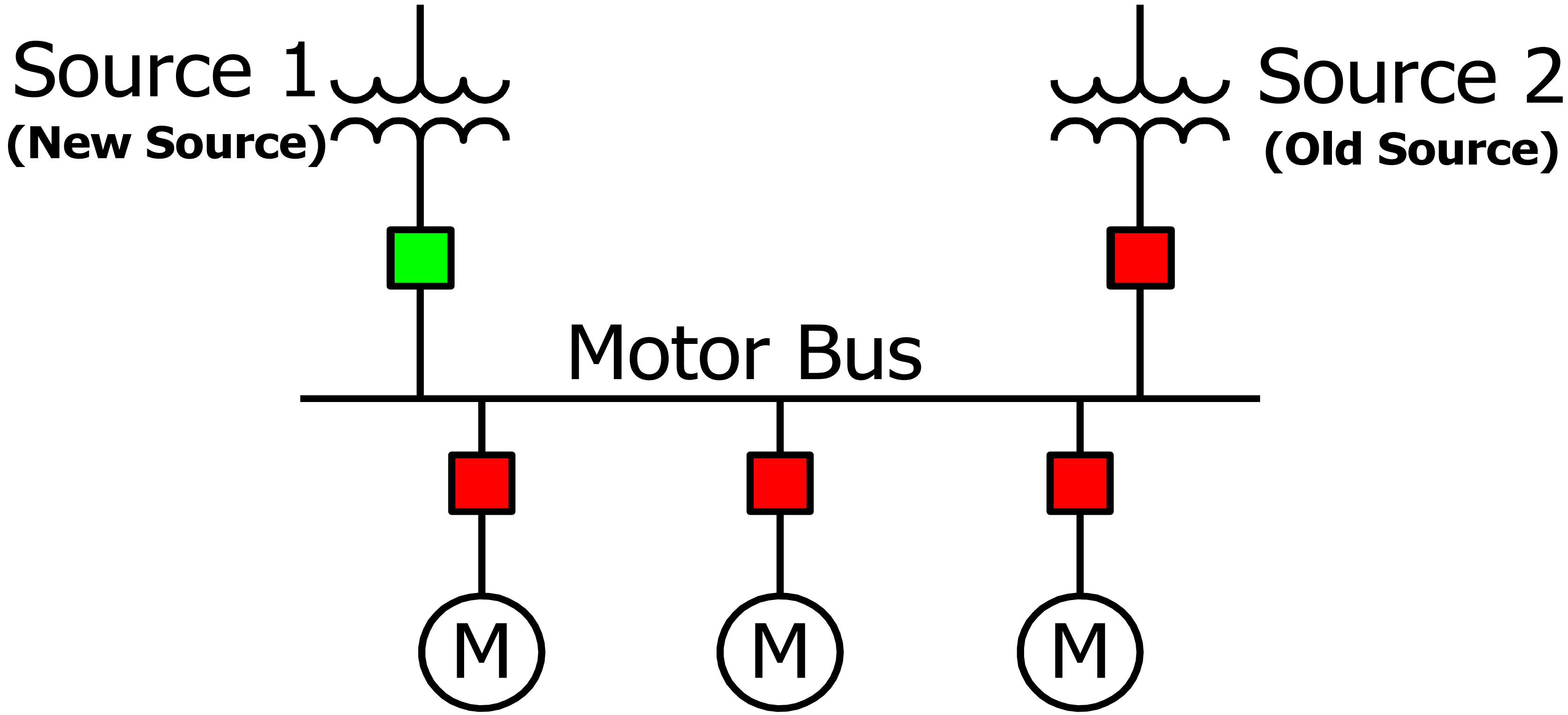
Closed Transition – Hot Parallel Transfer



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

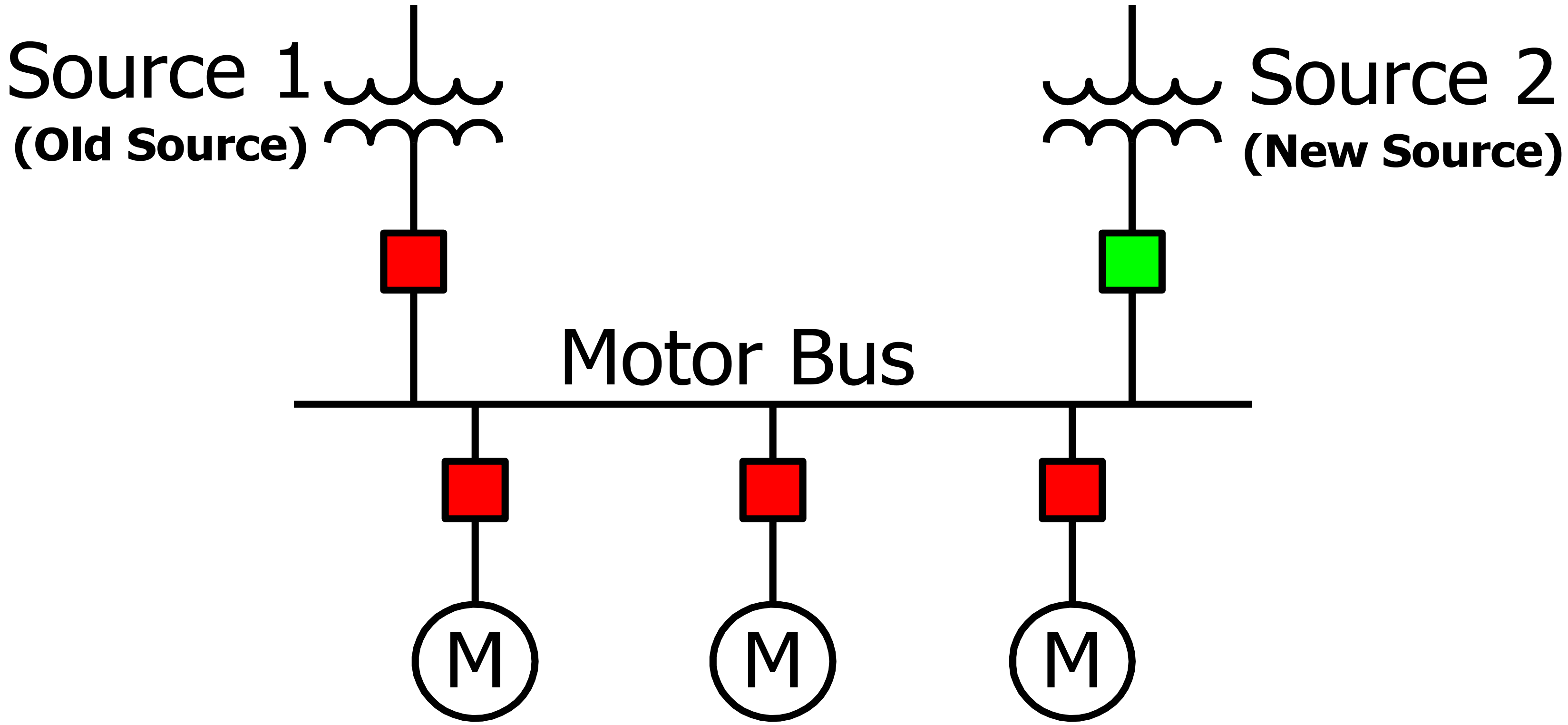
- Will not work during transient (emergency) conditions ***Do not want to connect "good" source to a source that is having problems.***
- Exposure to double-fed faults during parallel operation may violate the interrupt rating of the circuit breakers or the through-fault withstand ratings of source transformers and damage connected equipment
- 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

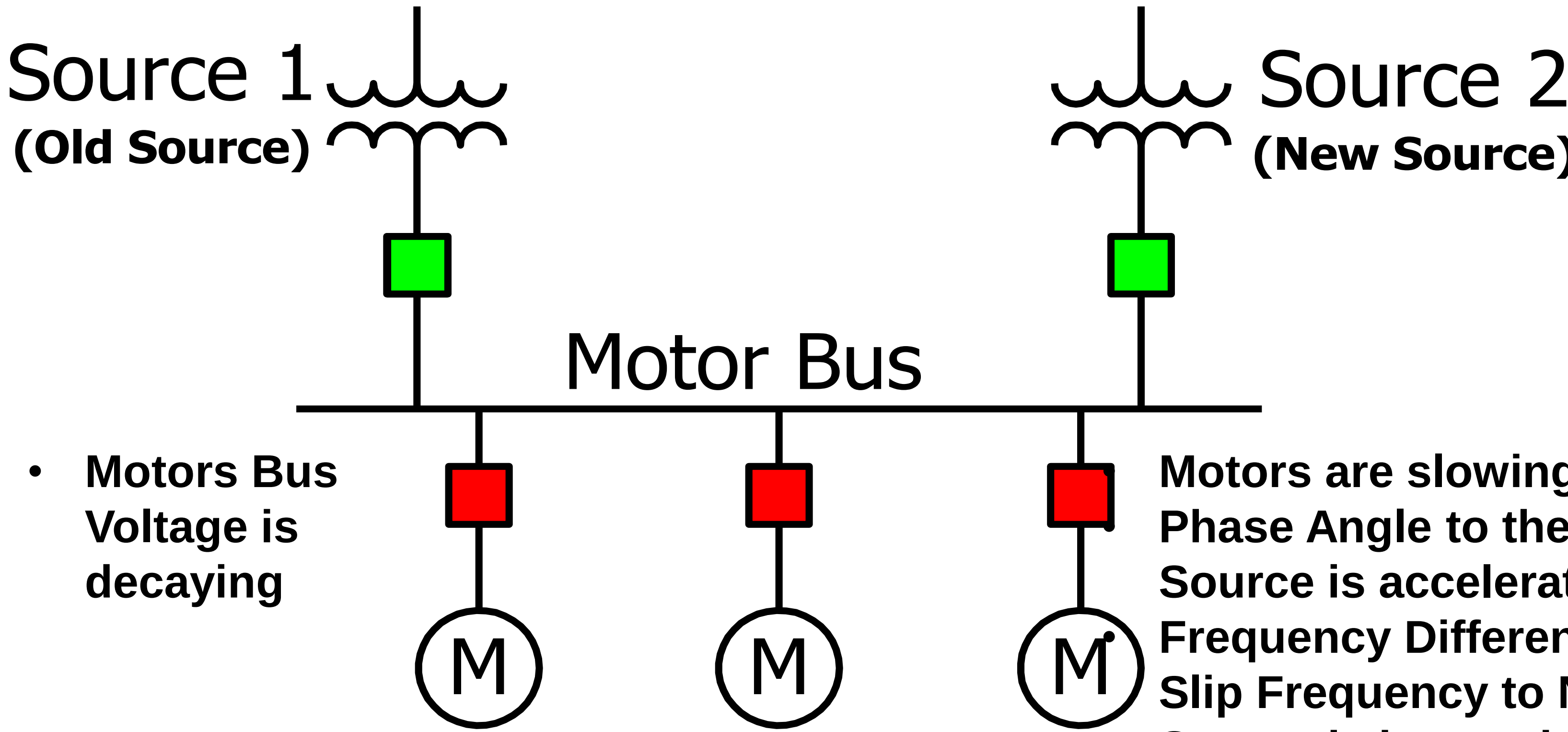
- Old Source Breaker is tripped before the New Source Breaker is closed.

- 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

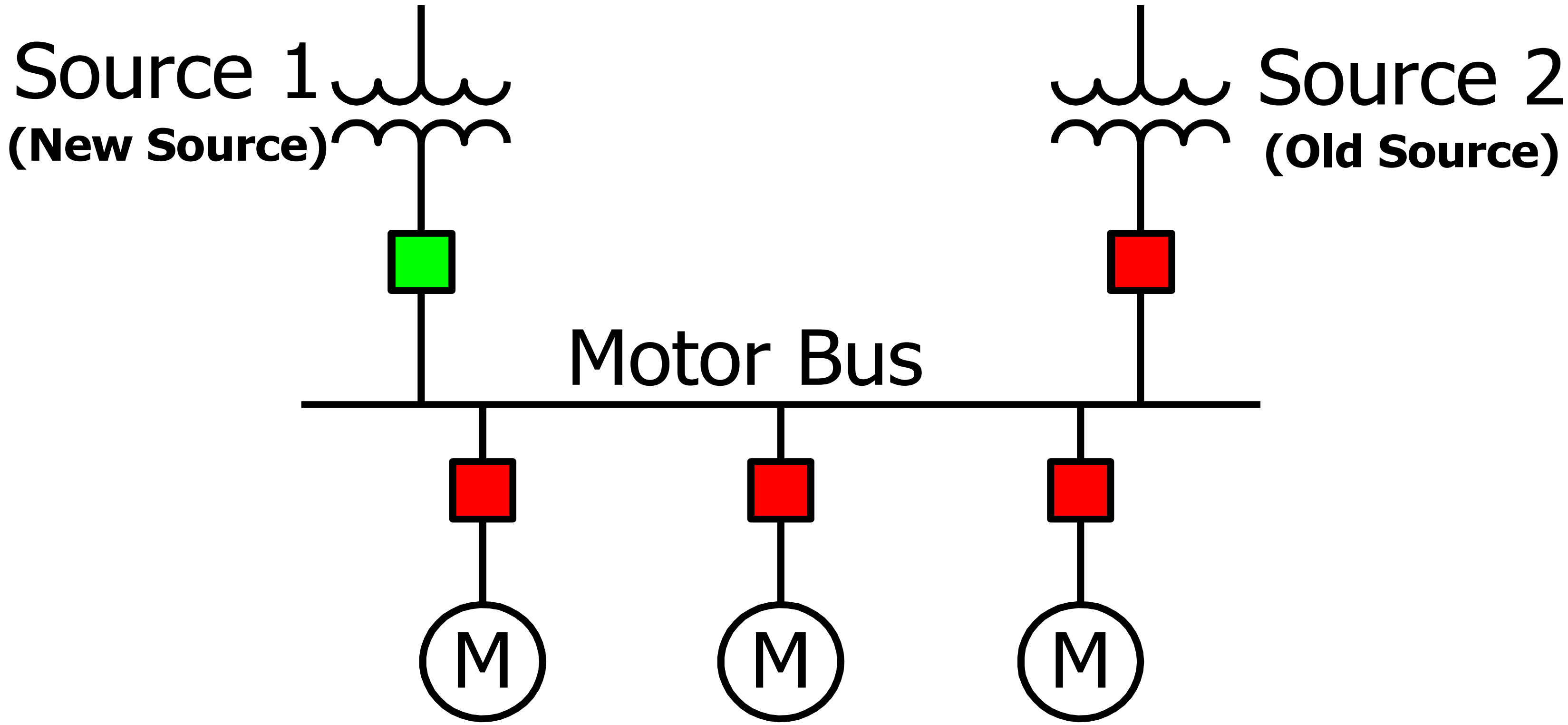


- **Motors Bus Voltage is decaying**

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

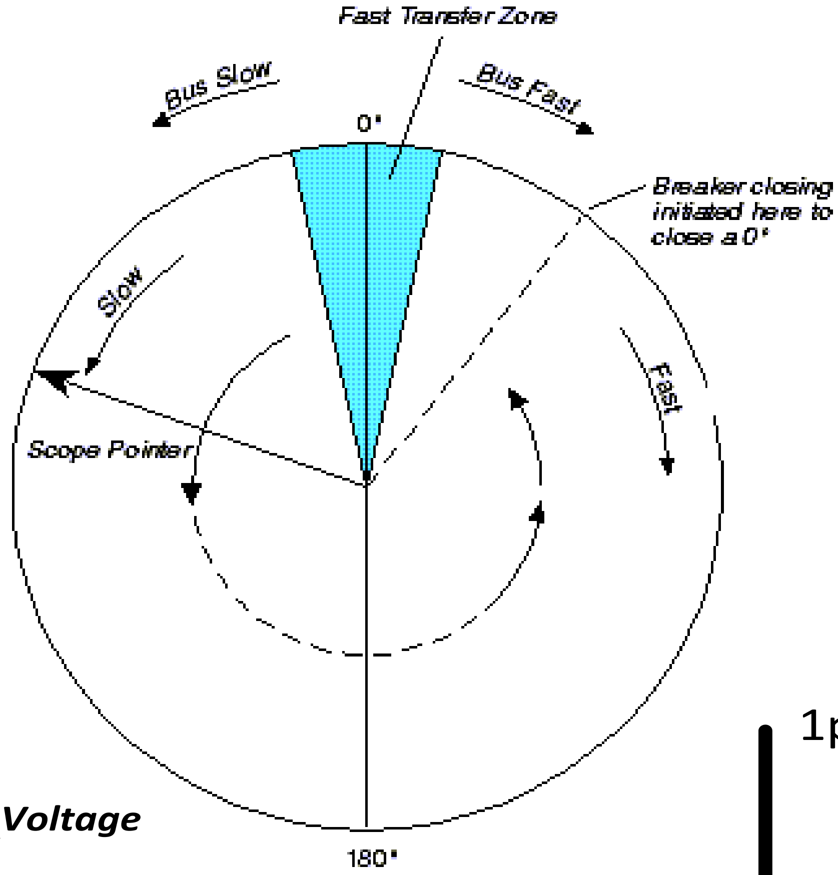
- **Slow Method that waits for the Motor Bus Voltage to decay below .30 per unit and ignores synchronism**
  - Residual Voltage Transfer
  - Like a roulette wheel; round and round she goes and where she stops nobody knows.

- **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

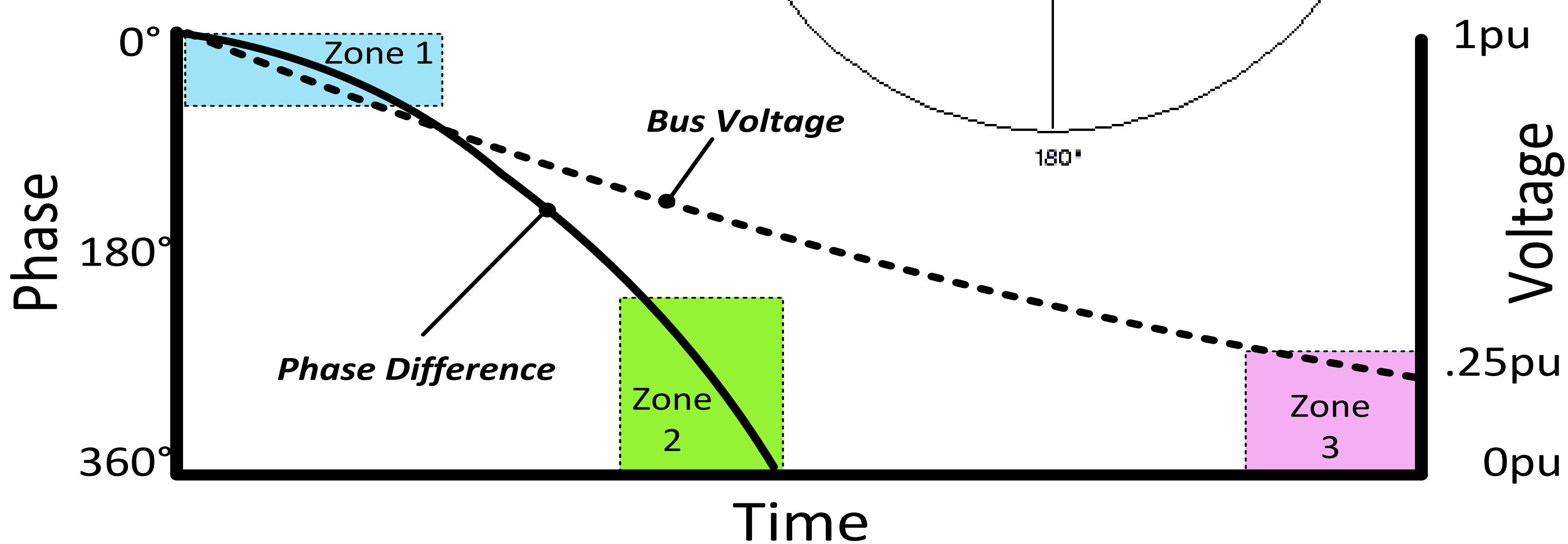
Motor Bus Transfer

Open Transition Methods:

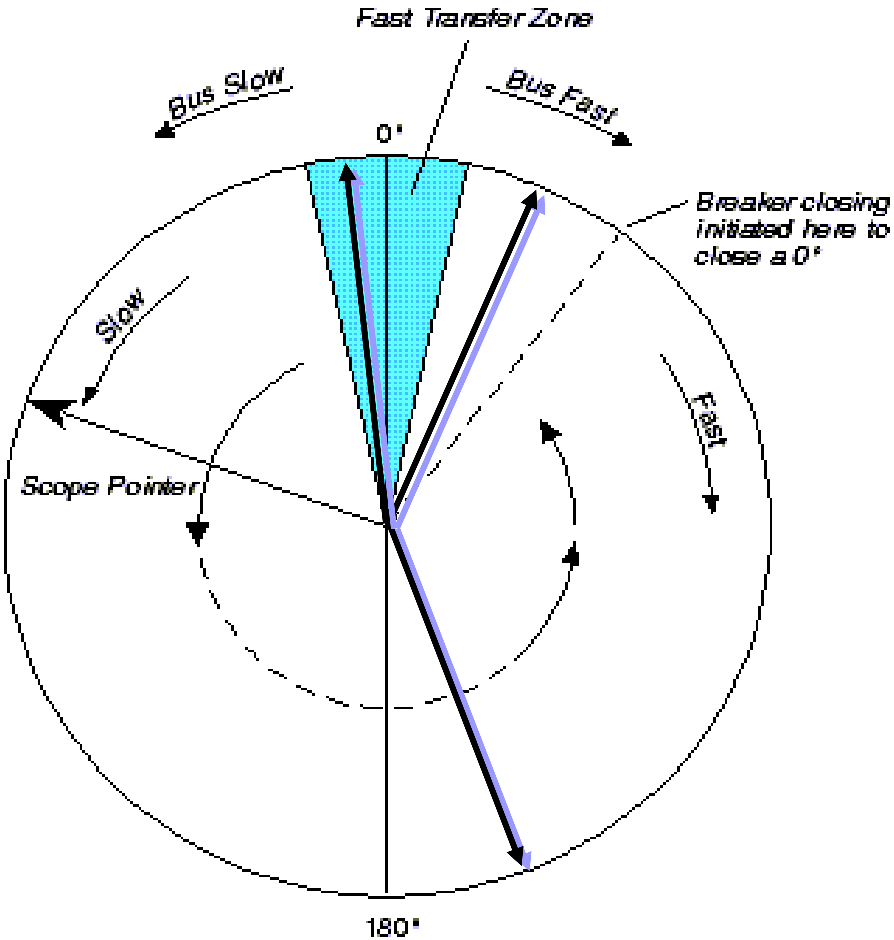
- Fast Transfer
- In-Phase Transfer
- Residual Voltage Transfer



Bus Transfer Zones

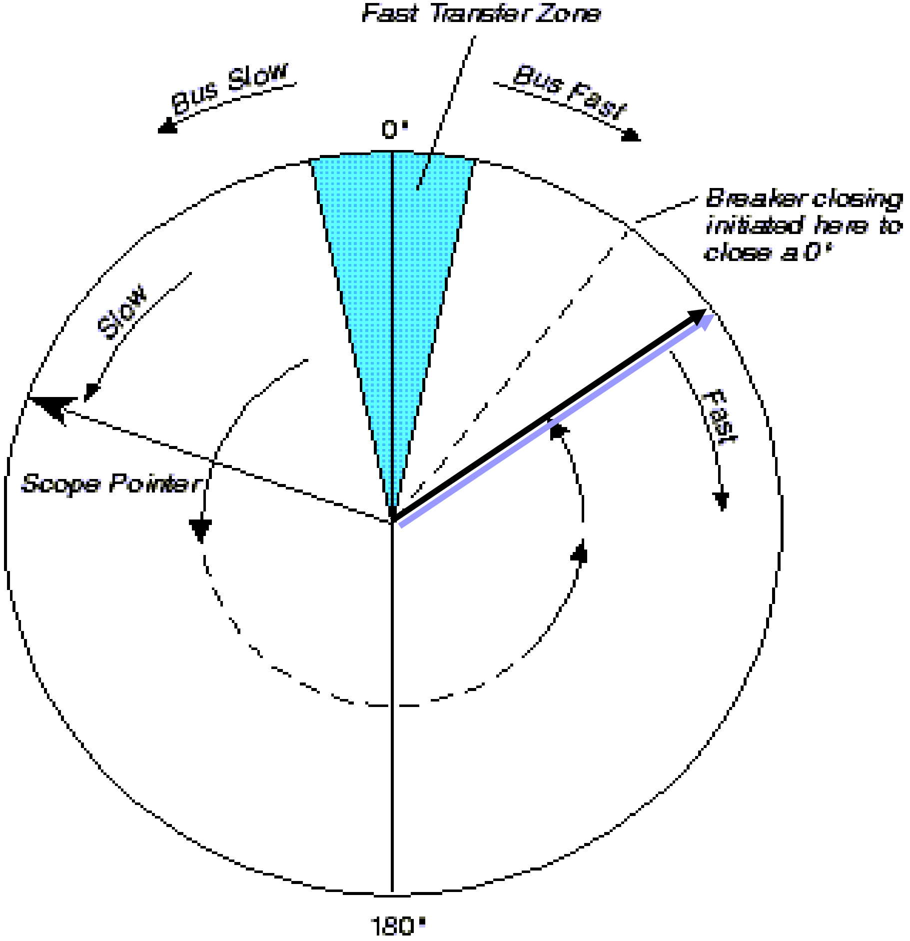


Fast Transfer Method



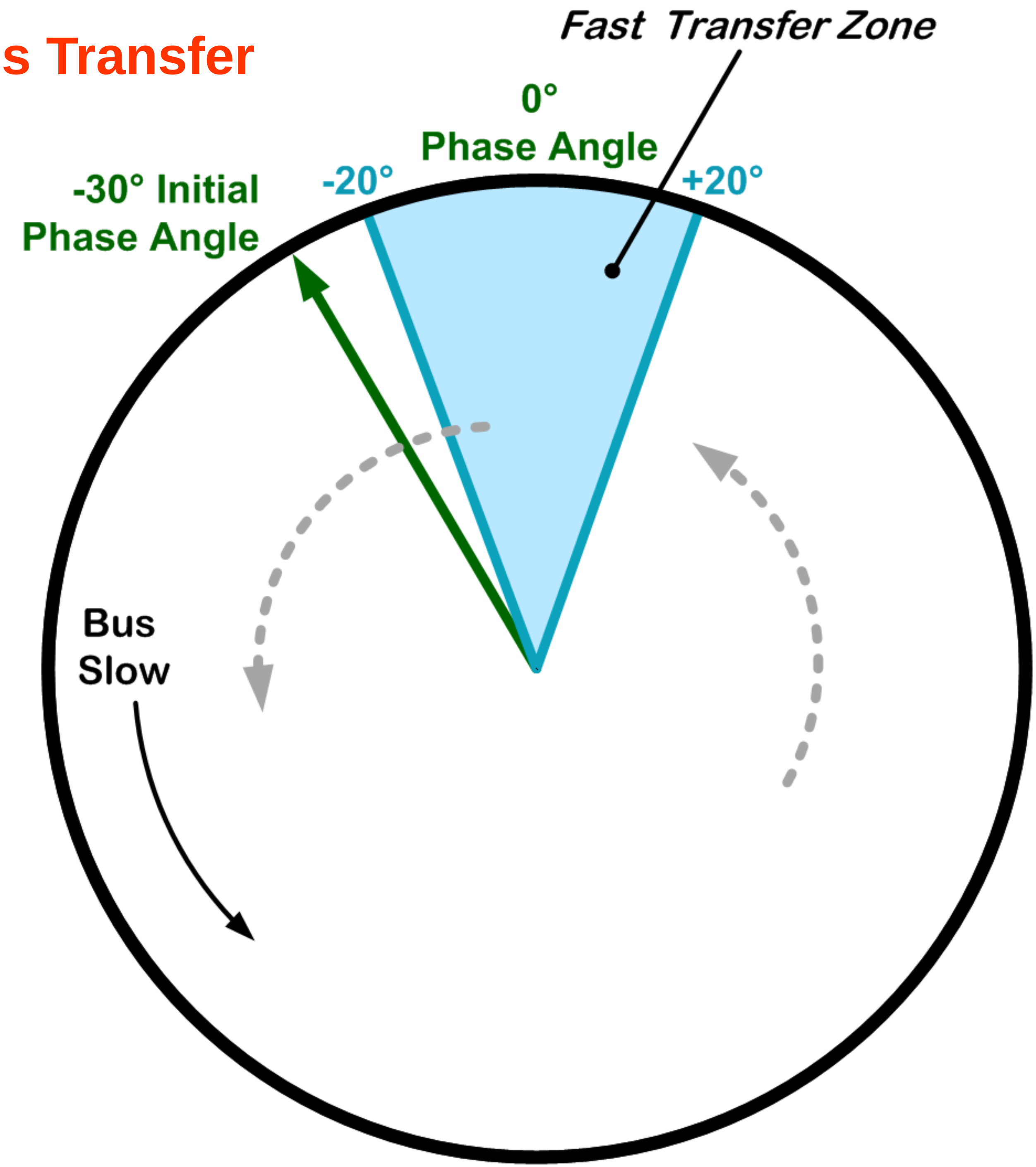
- New Source Breaker is closed if the phase angle between the Motor Bus and the New Source is within or moves into the Phase Angle Limit
- This method requires high-speed sync-check supervision
  - Must be able to block high speed
  - Must be able to close high speed
- Circuit breaker closing is also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

In-Phase Transfer Method

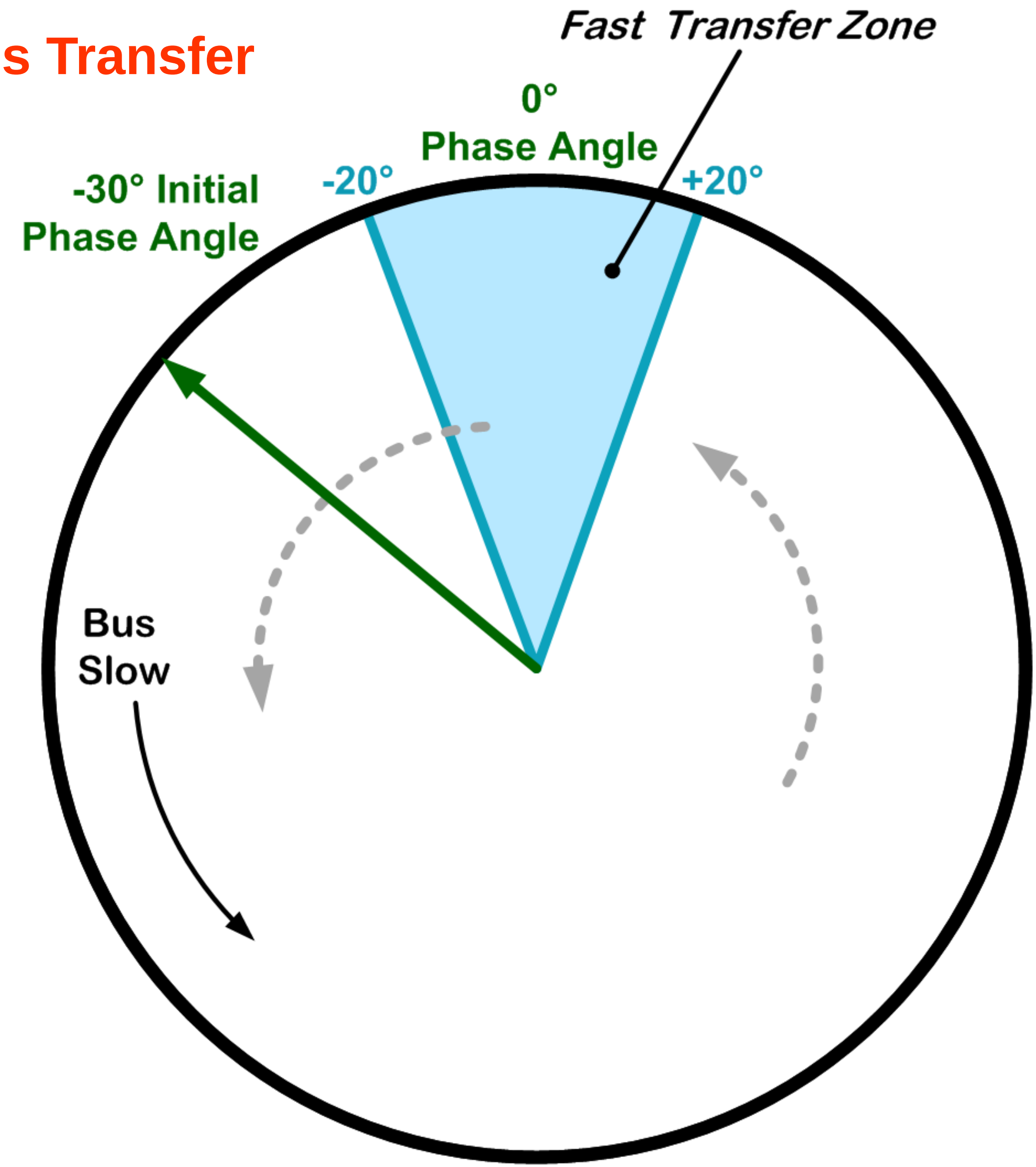


- Takes into account the **decaying motor bus frequency**, and the **increasing slip frequency** between the Motor Bus and the New Source
- Sends a New Source Breaker close command at an Advance Angle to compensate for the breaker close time so the motors are connected to the new source near zero degrees.

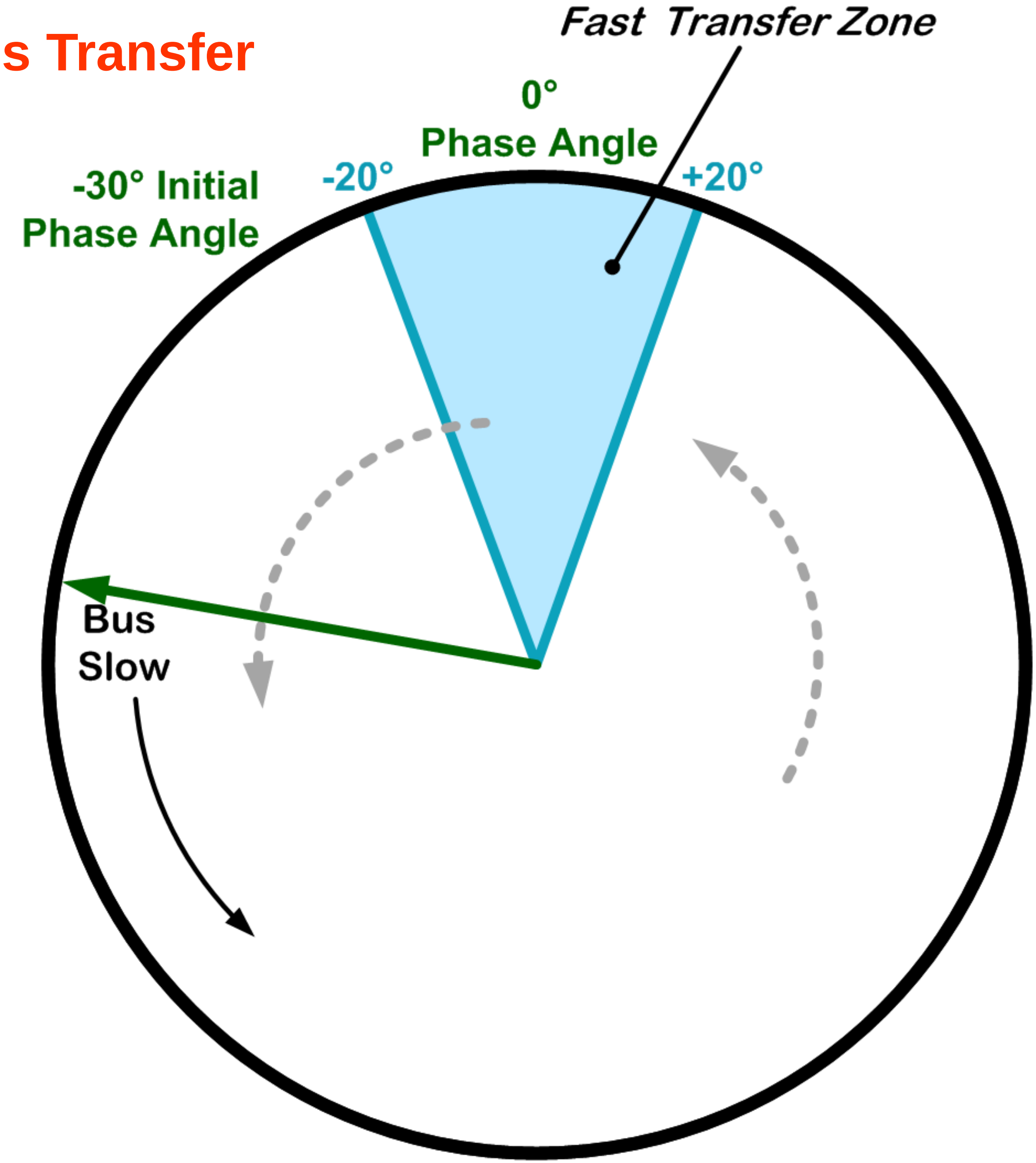
Motor Bus Transfer



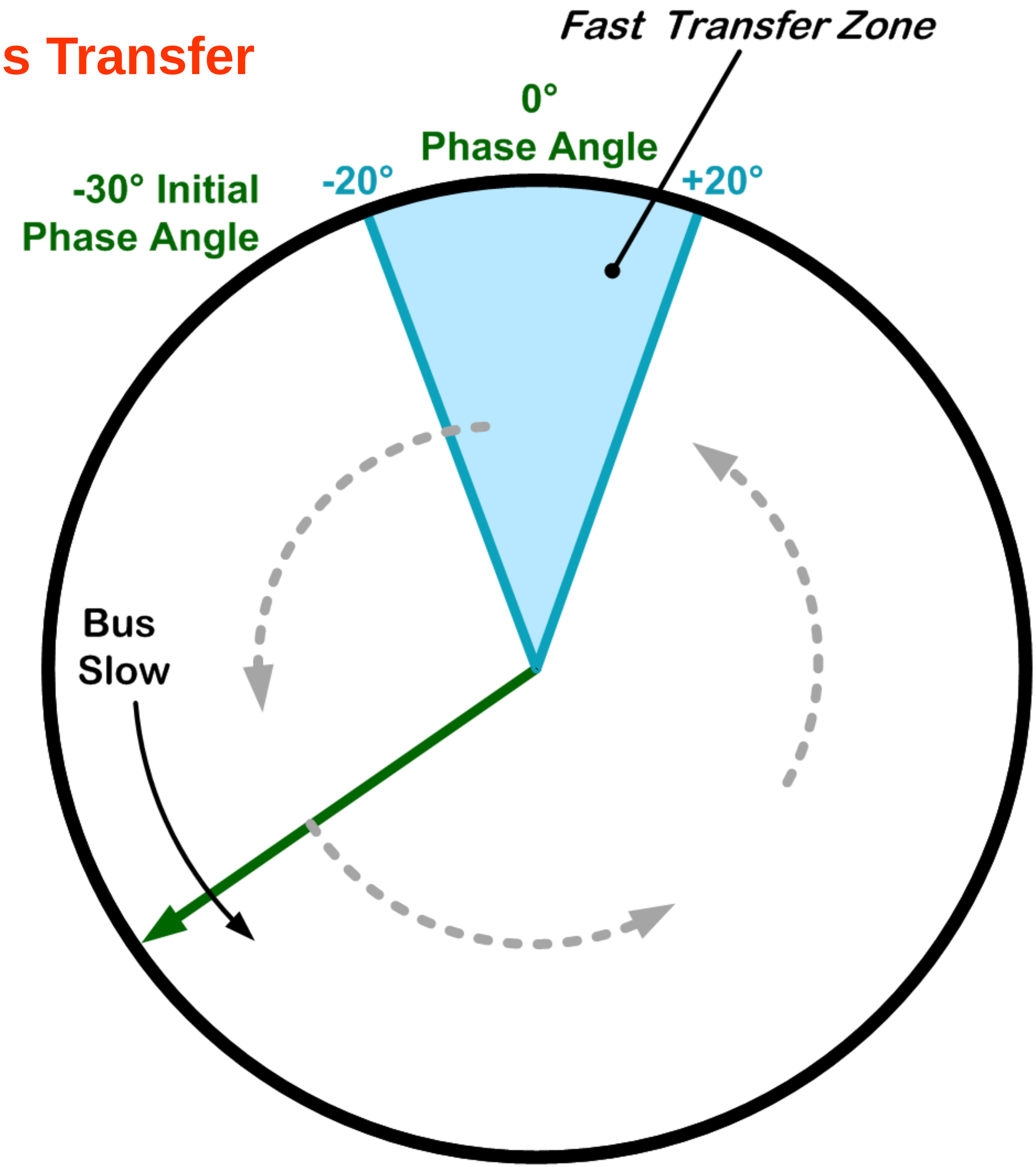
Motor Bus Transfer



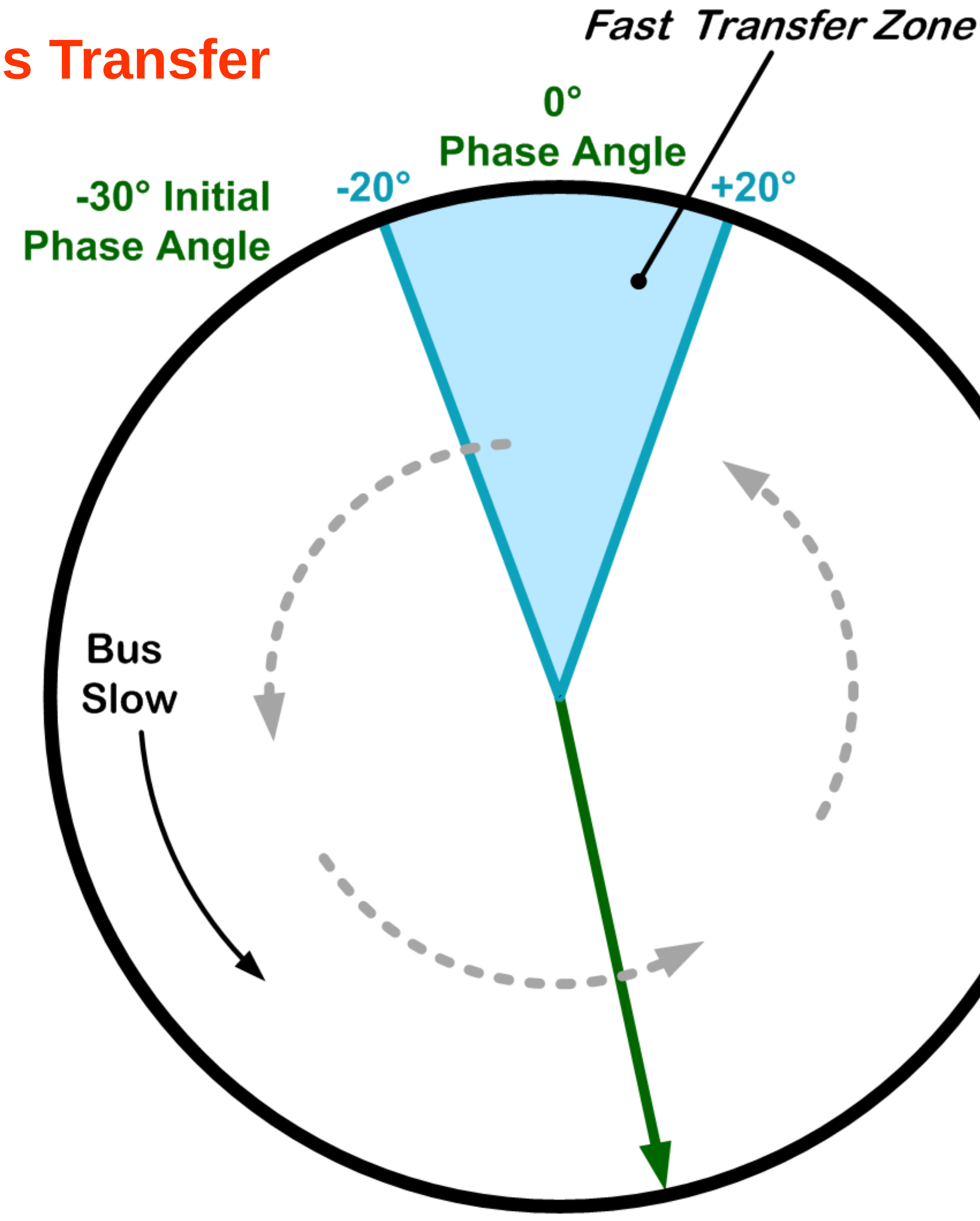
Motor Bus Transfer



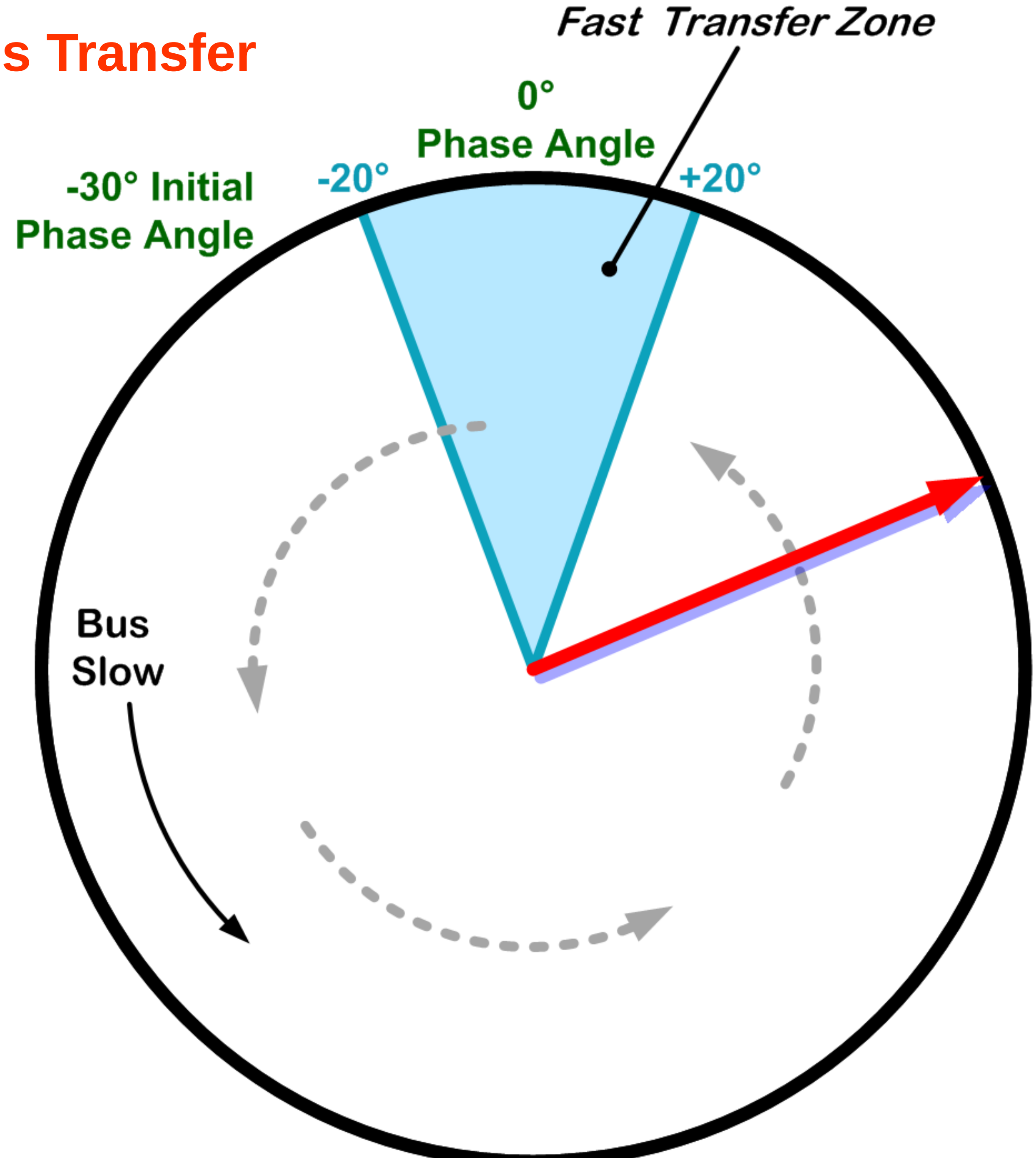
Motor Bus Transfer



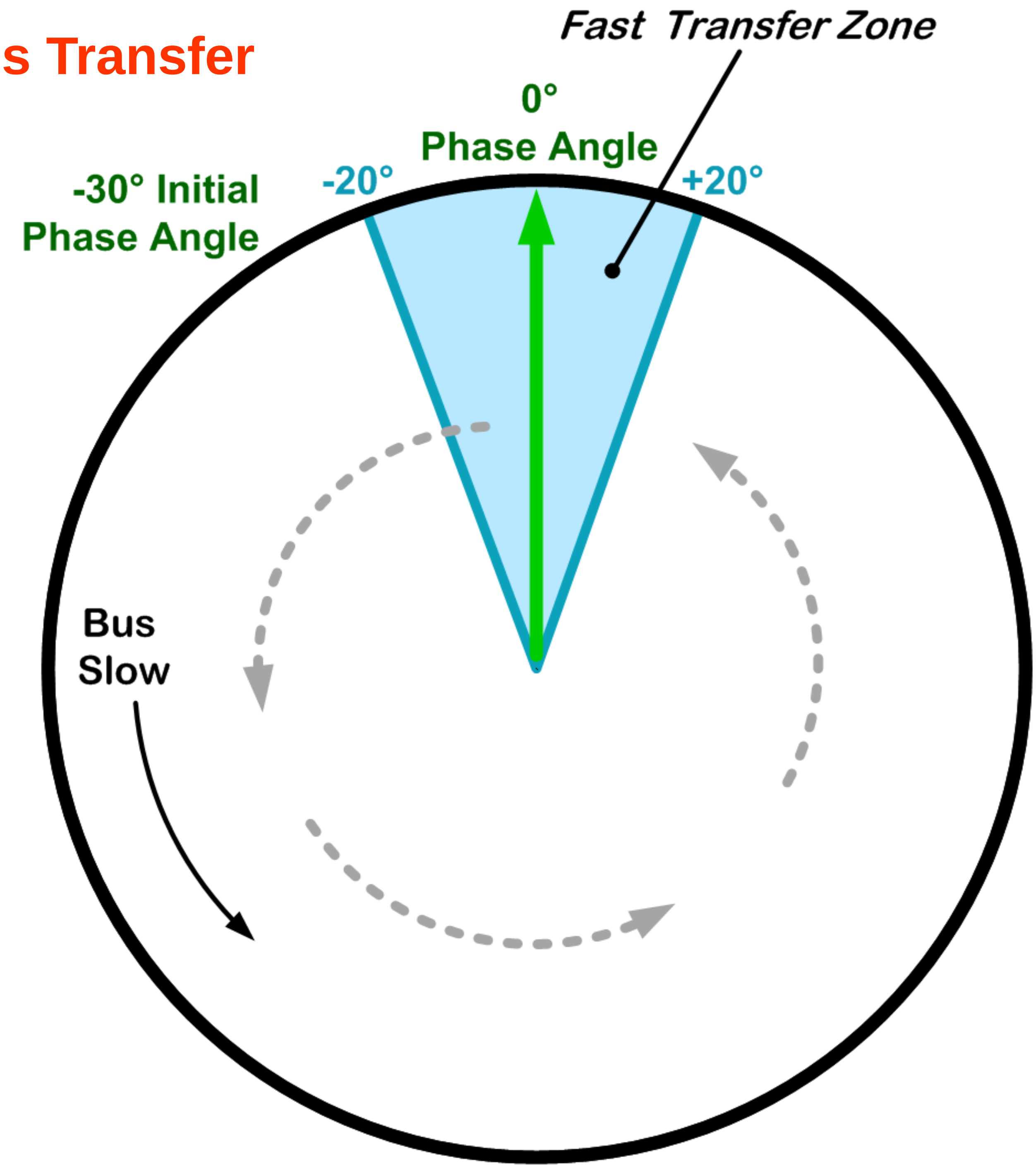
Motor Bus Transfer



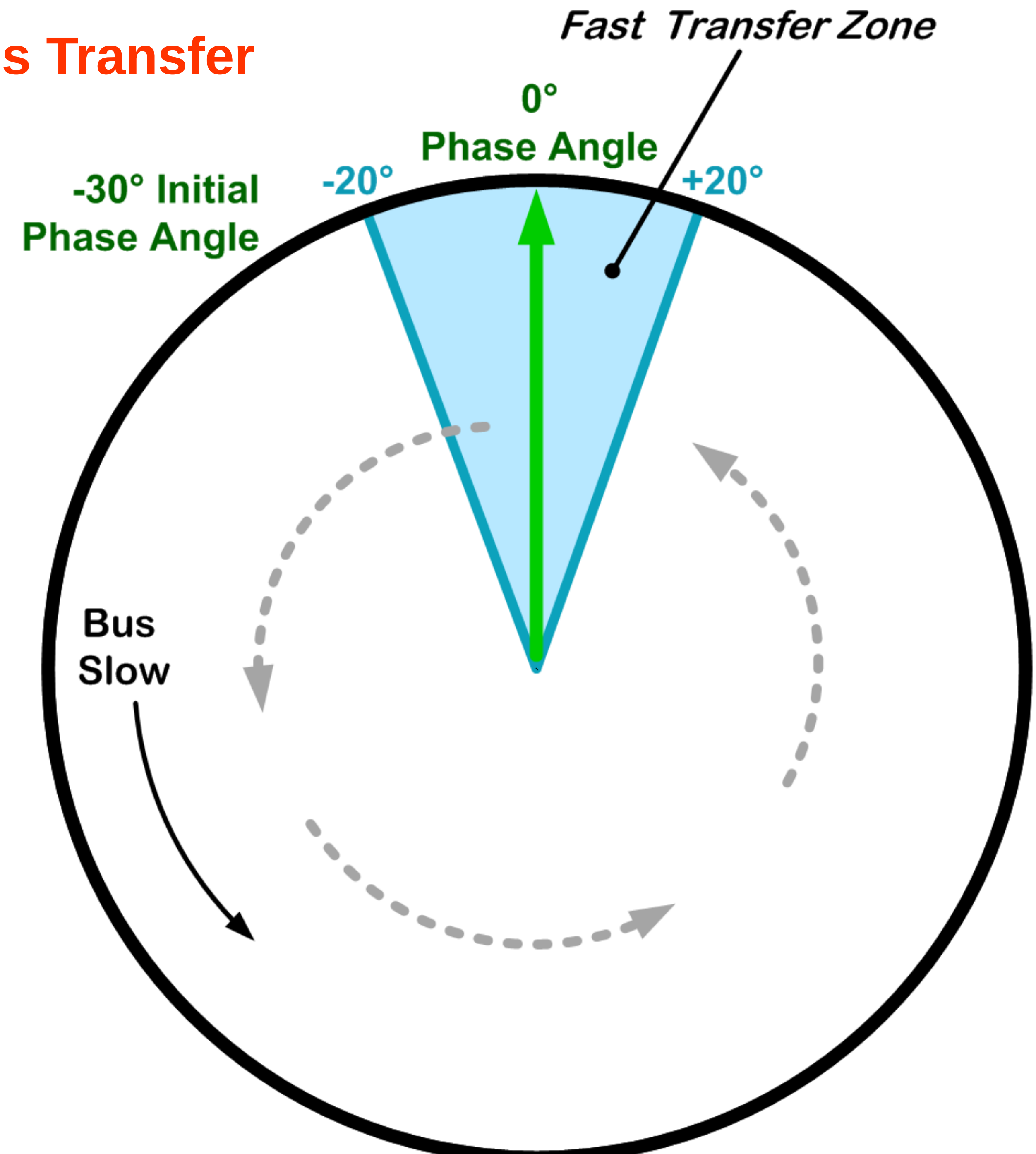
Motor Bus Transfer



Motor Bus Transfer



Motor Bus Transfer



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

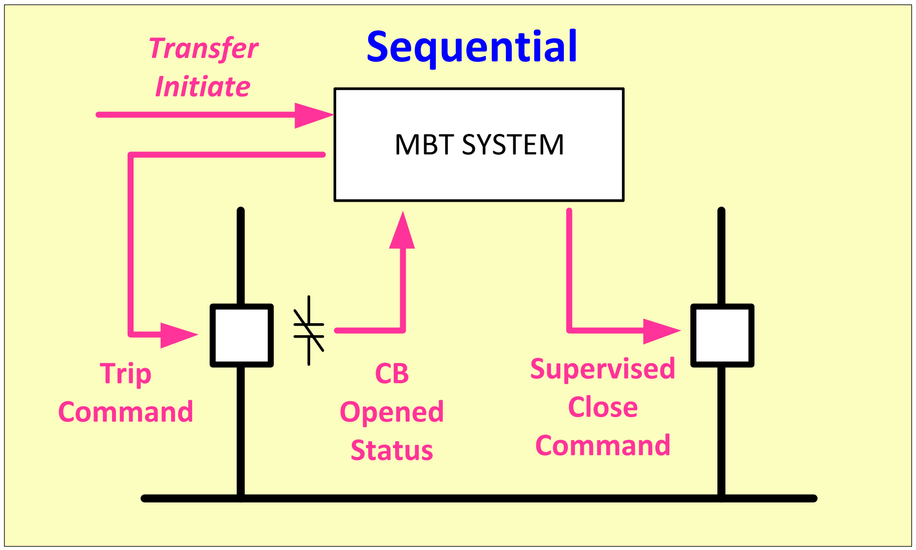
- **The new source breaker will be closed if the motor bus voltage drops below the Residual Voltage Transfer Limit**
- **IGNORES SYNCHRONISM**
- **Since phase angle and slip frequency is unsupervised, this method must prevent closure of the new source breaker until the motor bus voltage drops below a 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**

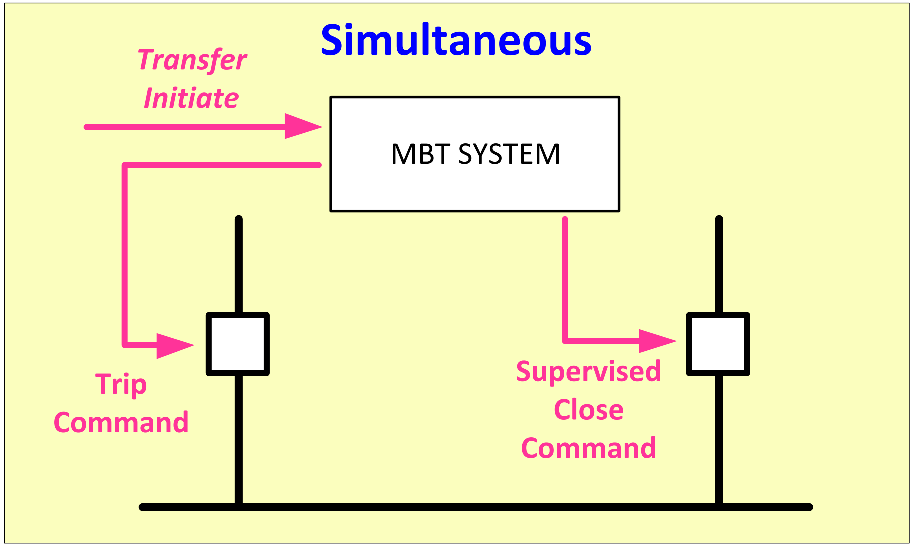
Residual Voltage Transfer Method

❑ 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):
  1. Motor bus frequency may have already decayed past the stall point of motors on the bus.
  2. If the new source cannot re-accelerate all bus motors simultaneously.
  3. 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!**

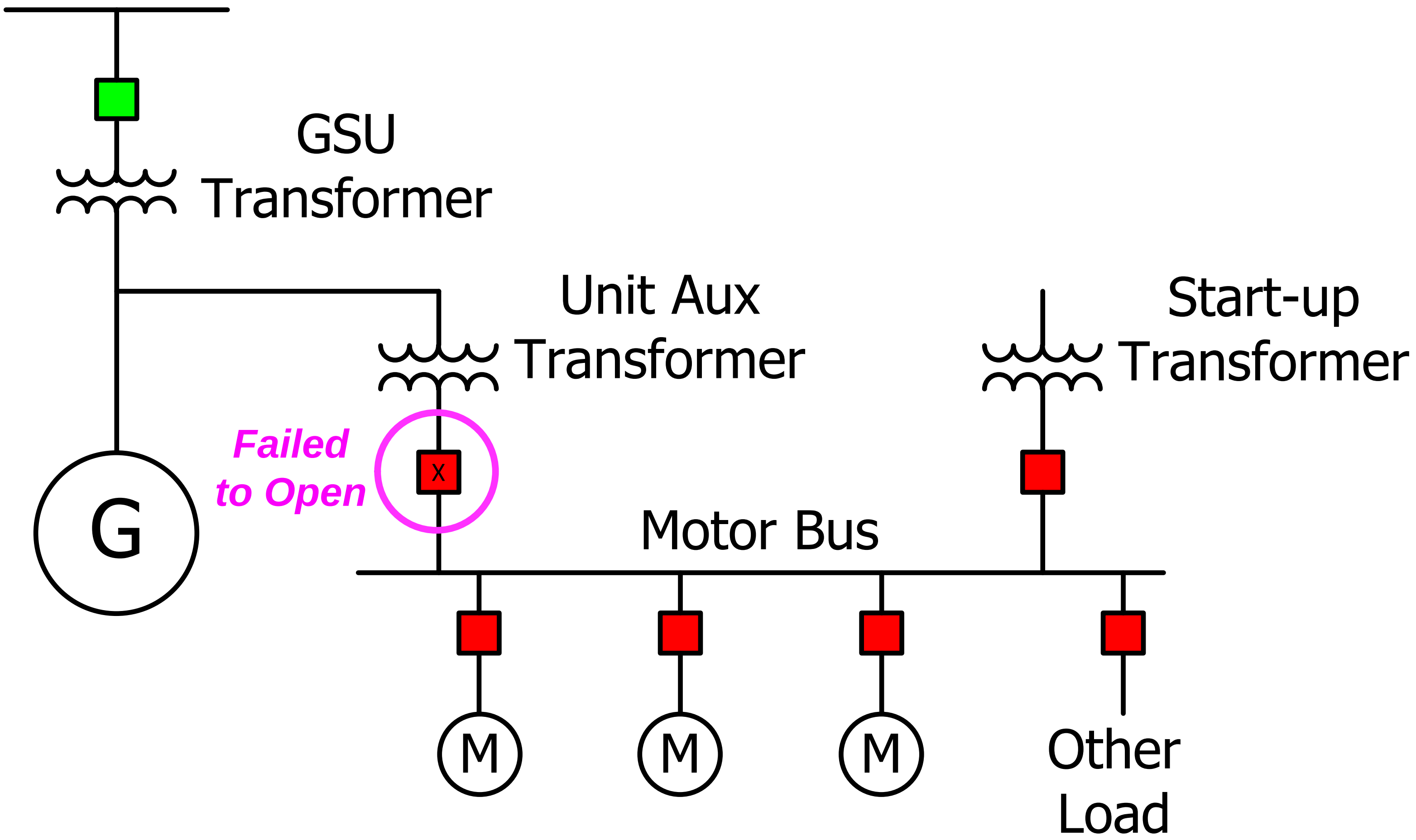
Open Transition Modes:
Sequential & Simultaneous





Open Transition – Simultaneous Mode

Breaker Failure



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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.

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

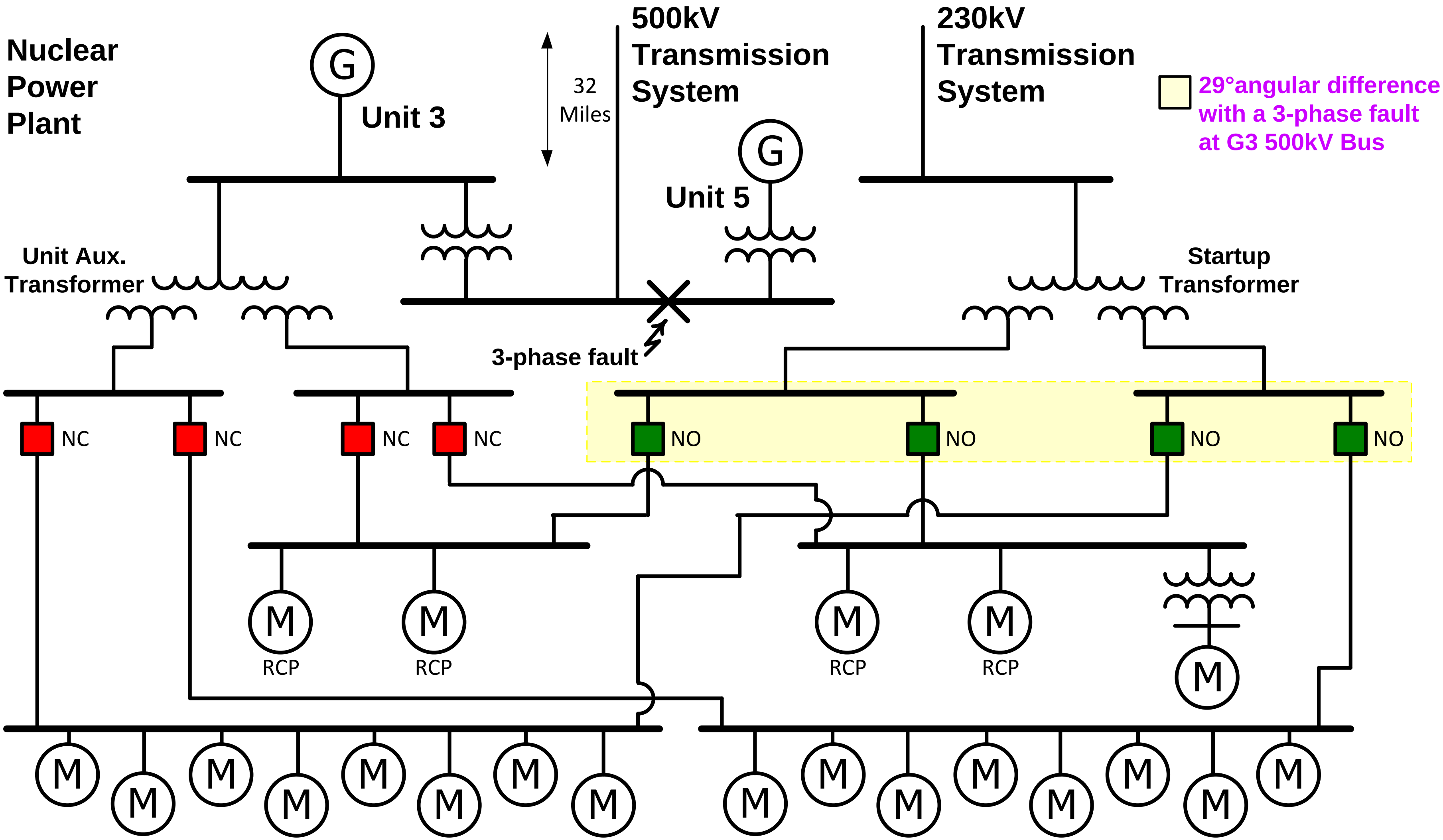
… there could be an inherent phase shift (30°), between the main and alternate source based on the transformer configuration of the two sources.

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.”

Motor Bus Transfer



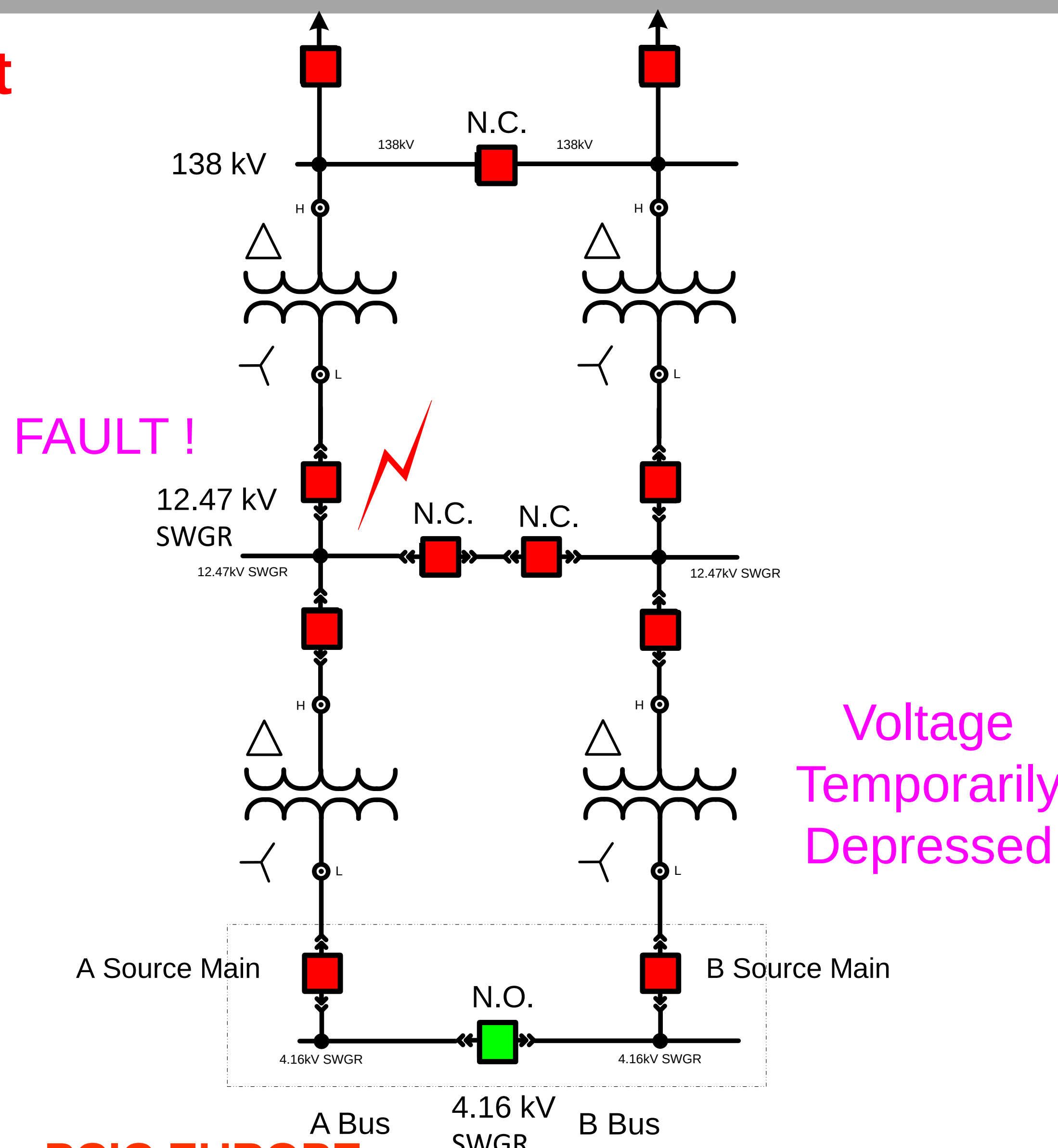
Electromechanical Synchronism-Check Relay Test

- 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 (ΔF) and measure the blocking time and blocking angle.
- Tests were run for the following conditions:

TEST DATA

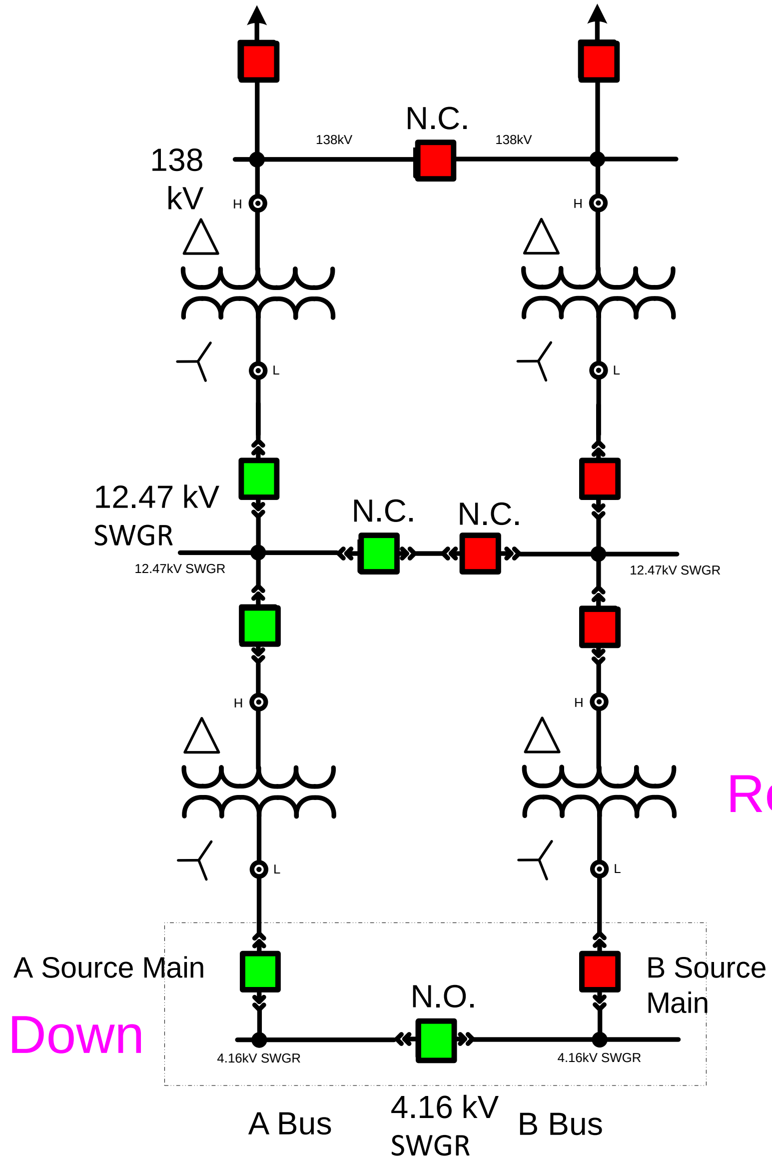
Δ F (FREQUENCY)	Tblock	ϕ Block
0.05 Hz	1600 Msec	27.18°
0.10 Hz	1000 Msec	40.32°
0.15 Hz	800 Msec	48.42°
0.20 Hz	600 Msec	47.34°
0.25 Hz	550 Msec	54.00°
0.30 Hz	500 Msec	60.48°
0.35 Hz	450 Msec	63.00°
0.40 Hz	420 Msec	68.22°
0.45 Hz	360 Msec	67.86°
0.50 Hz	320 Msec	73.62°

Industrial Redundant Incoming Source



Motor Bus Transfer

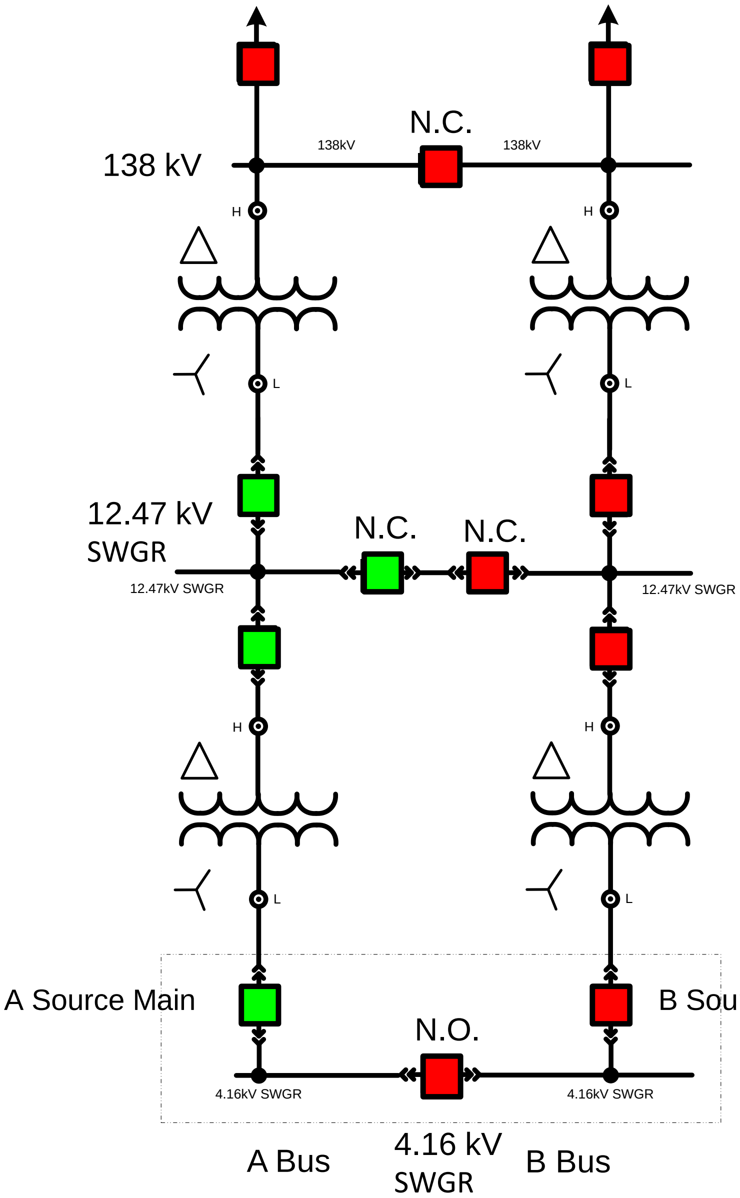
Industrial Redundant Incoming Source



Voltage Recovering

Motors Spinning Down

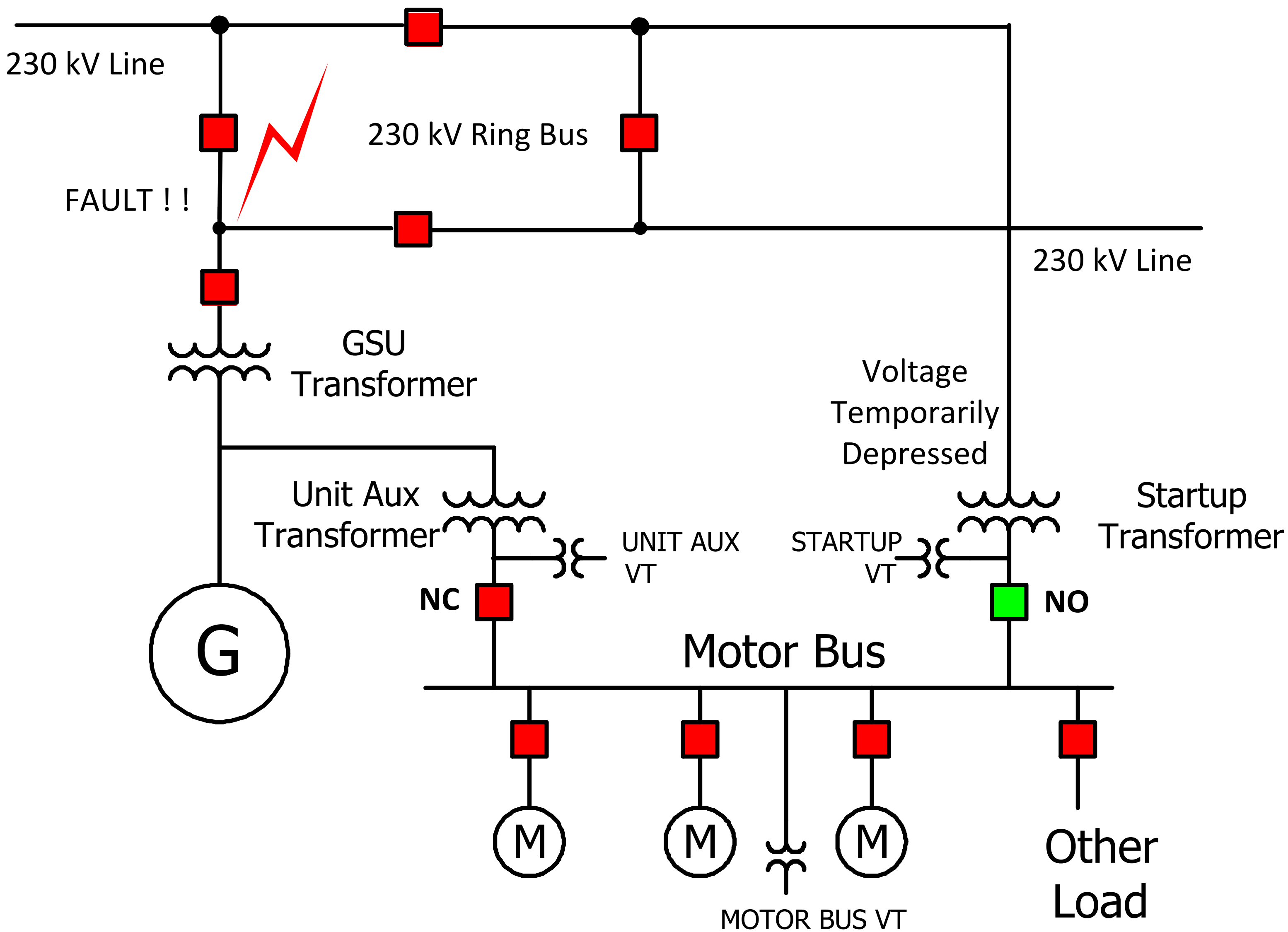
Industrial Redundant Incoming Source



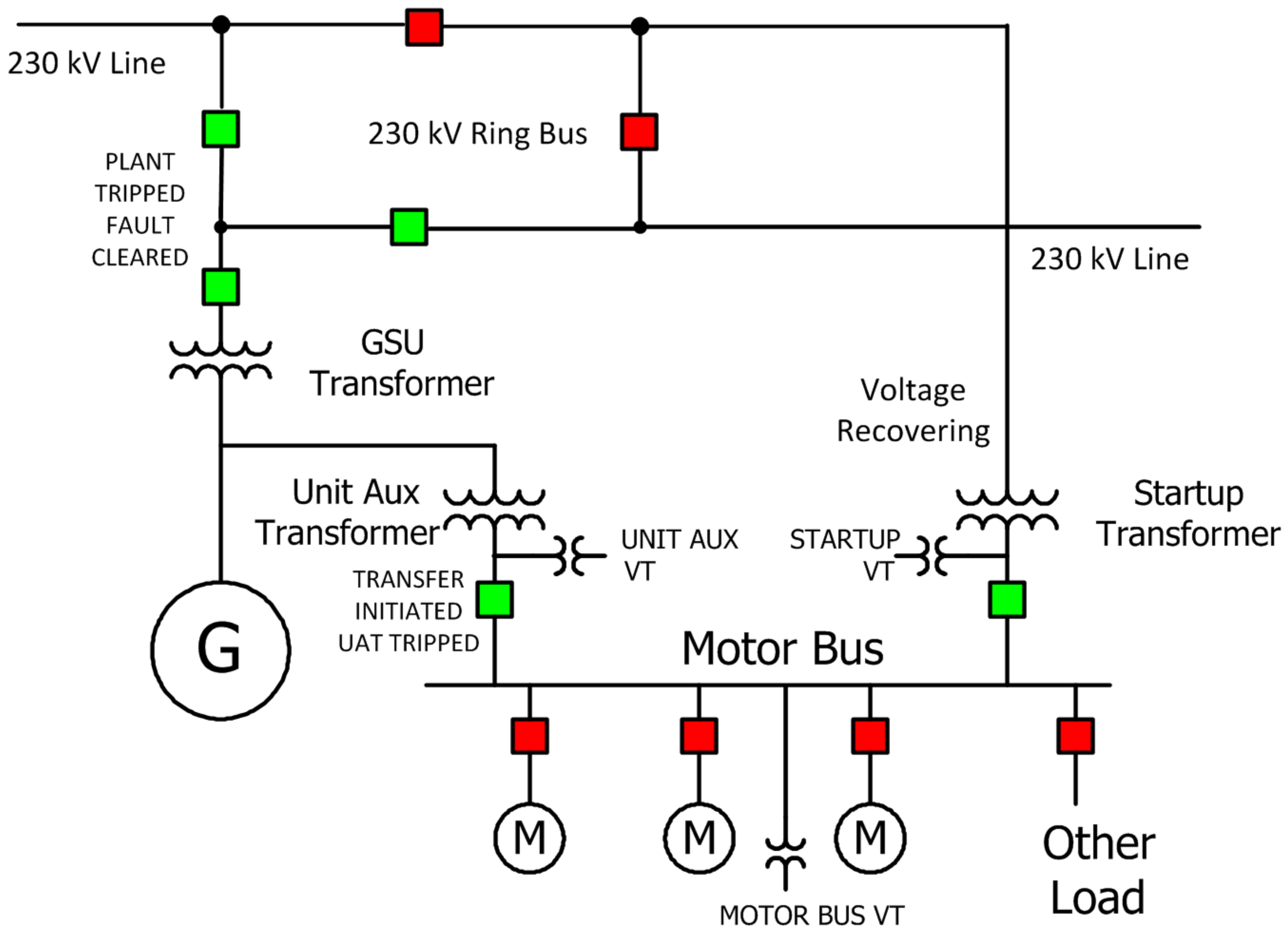
Voltage Recovers

SYNCHRONOUS TRANSFER COMPLETED

Fault at Generating Station

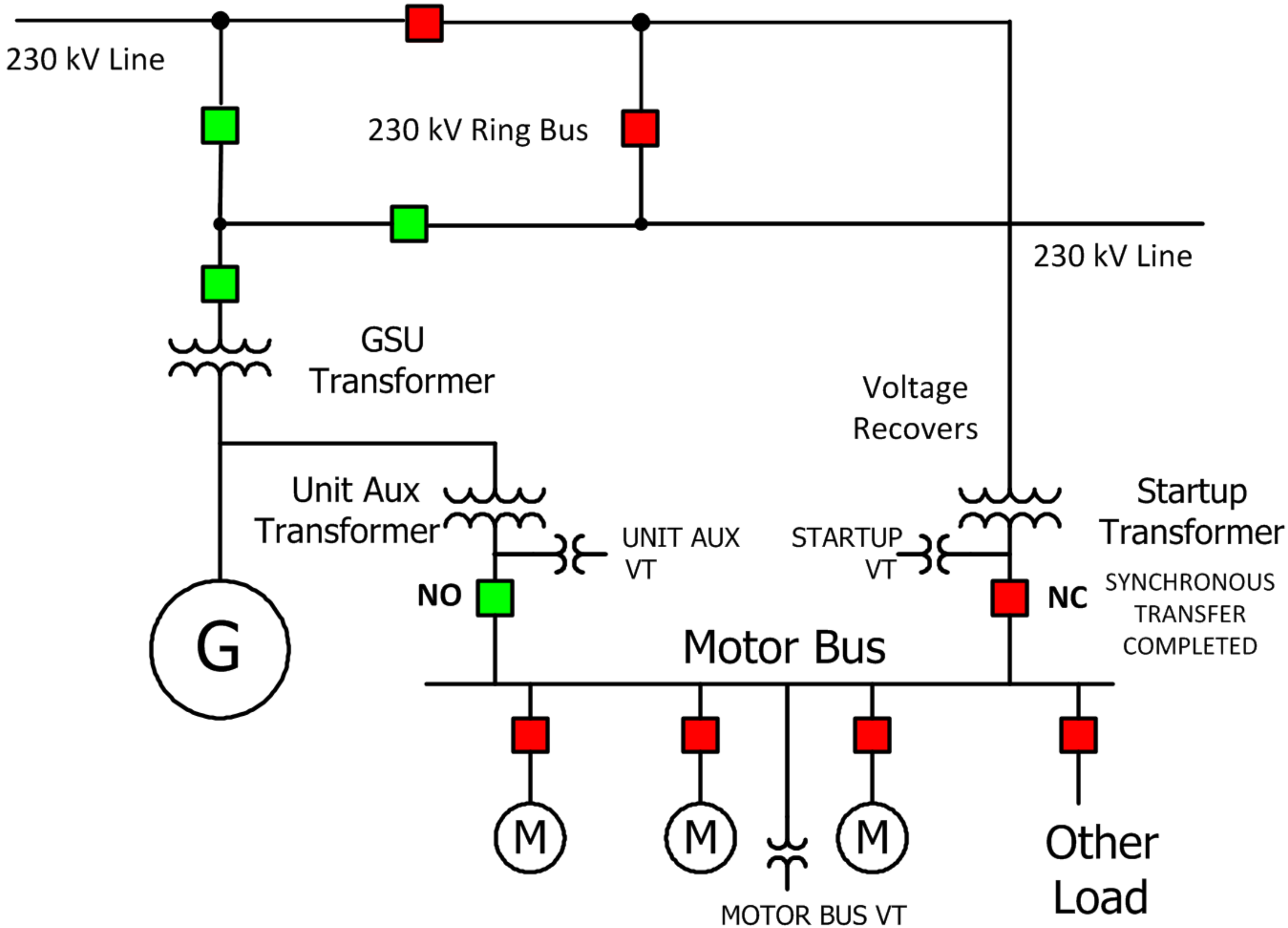


Fault at Generating Station

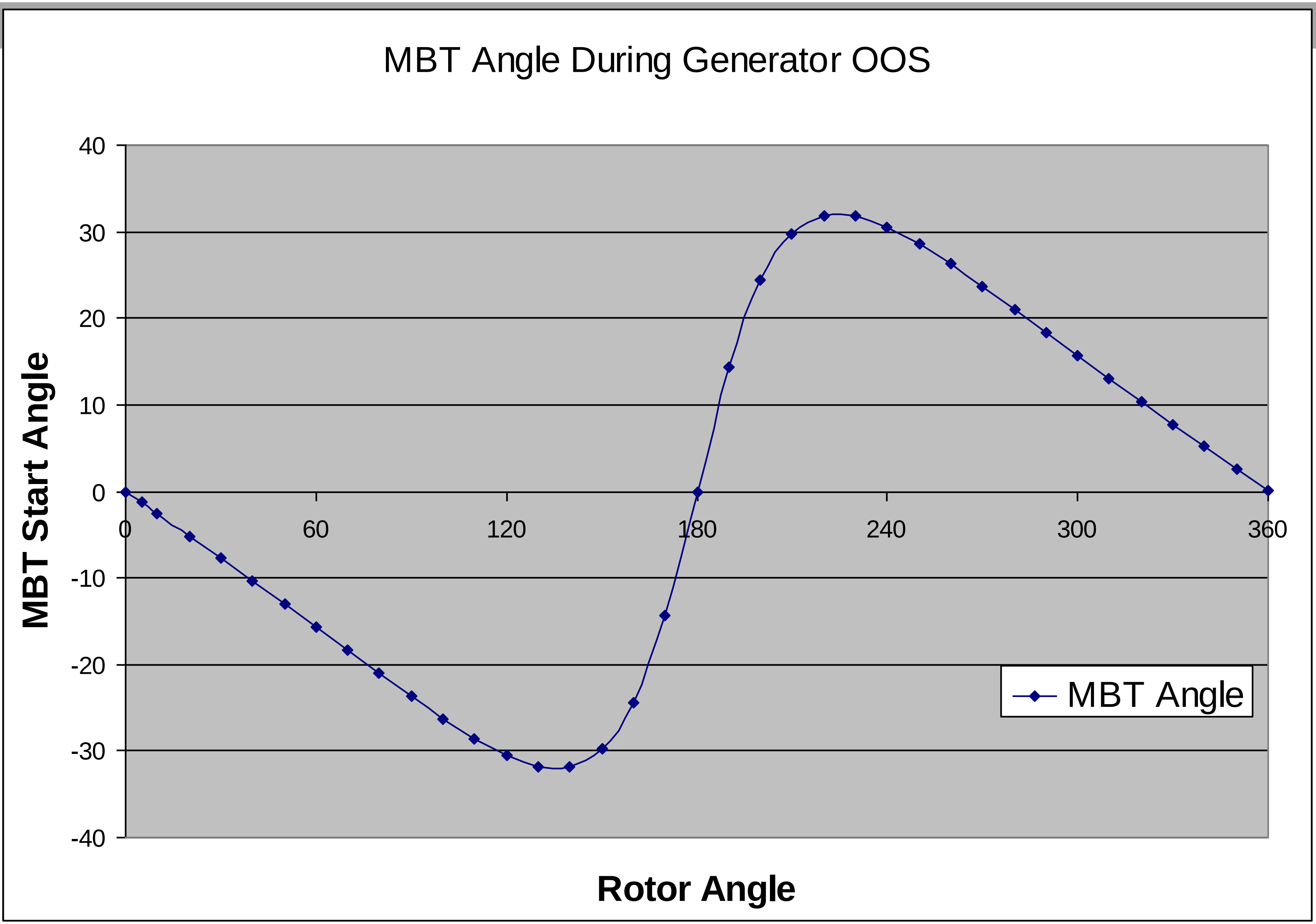


Motor Bus Transfer

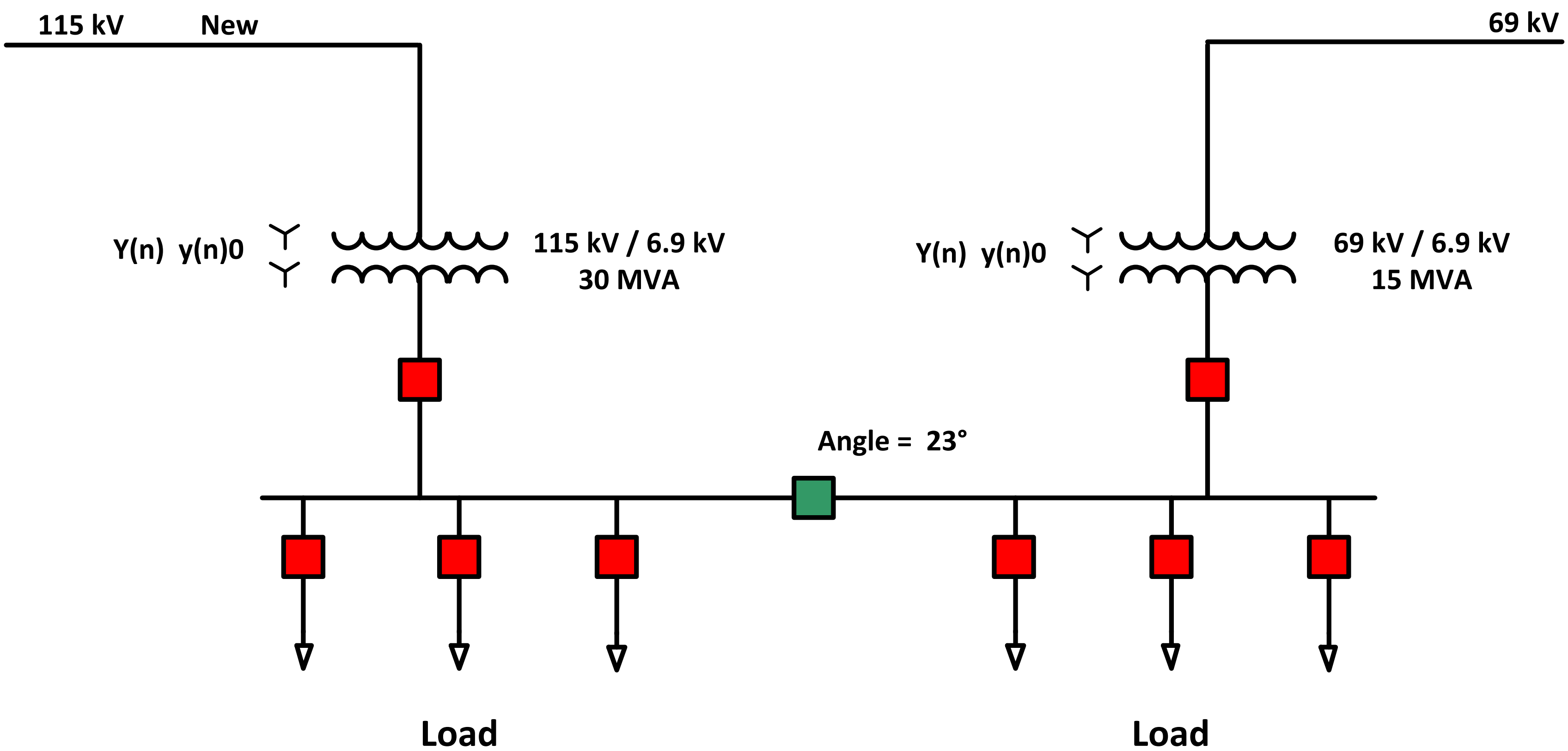
Fault at Generating Station



Motor Bus Transfer



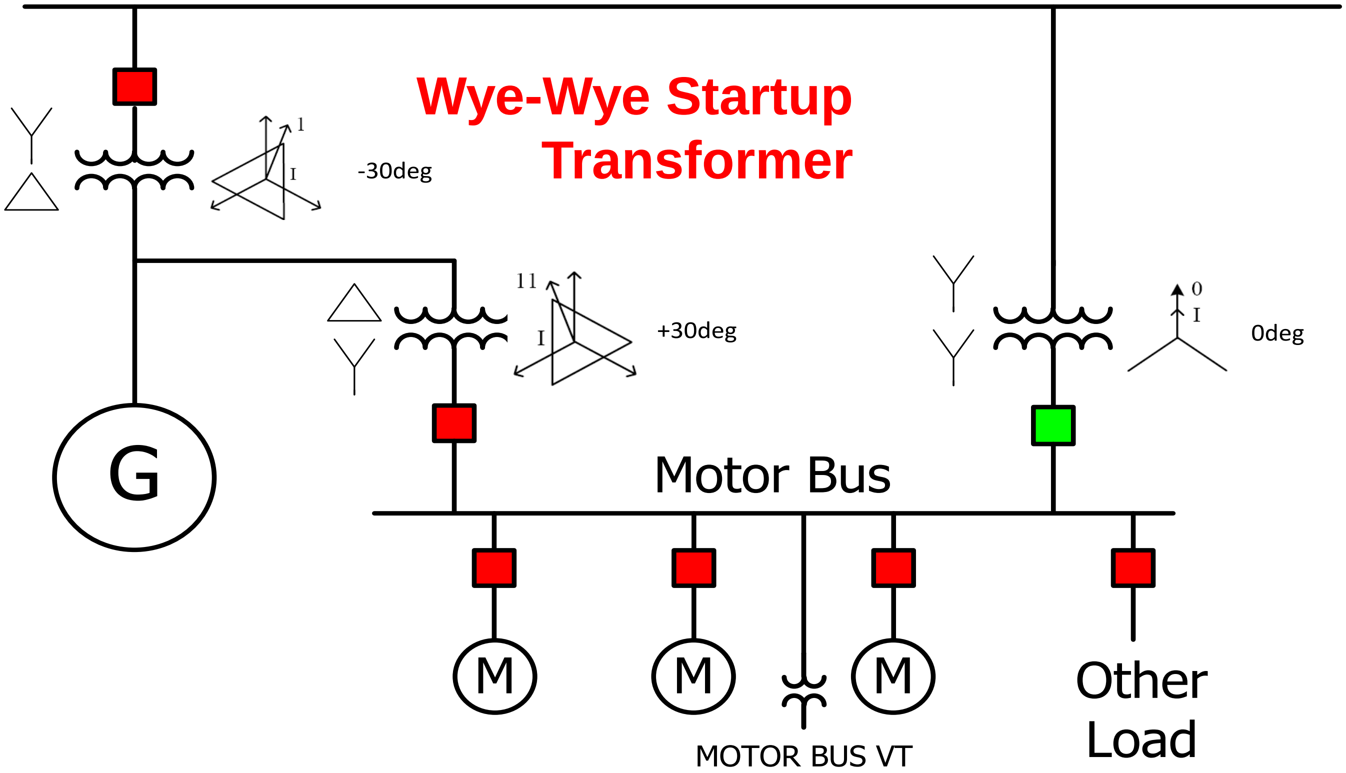
Motor Bus Transfer



Petrochemical Plant

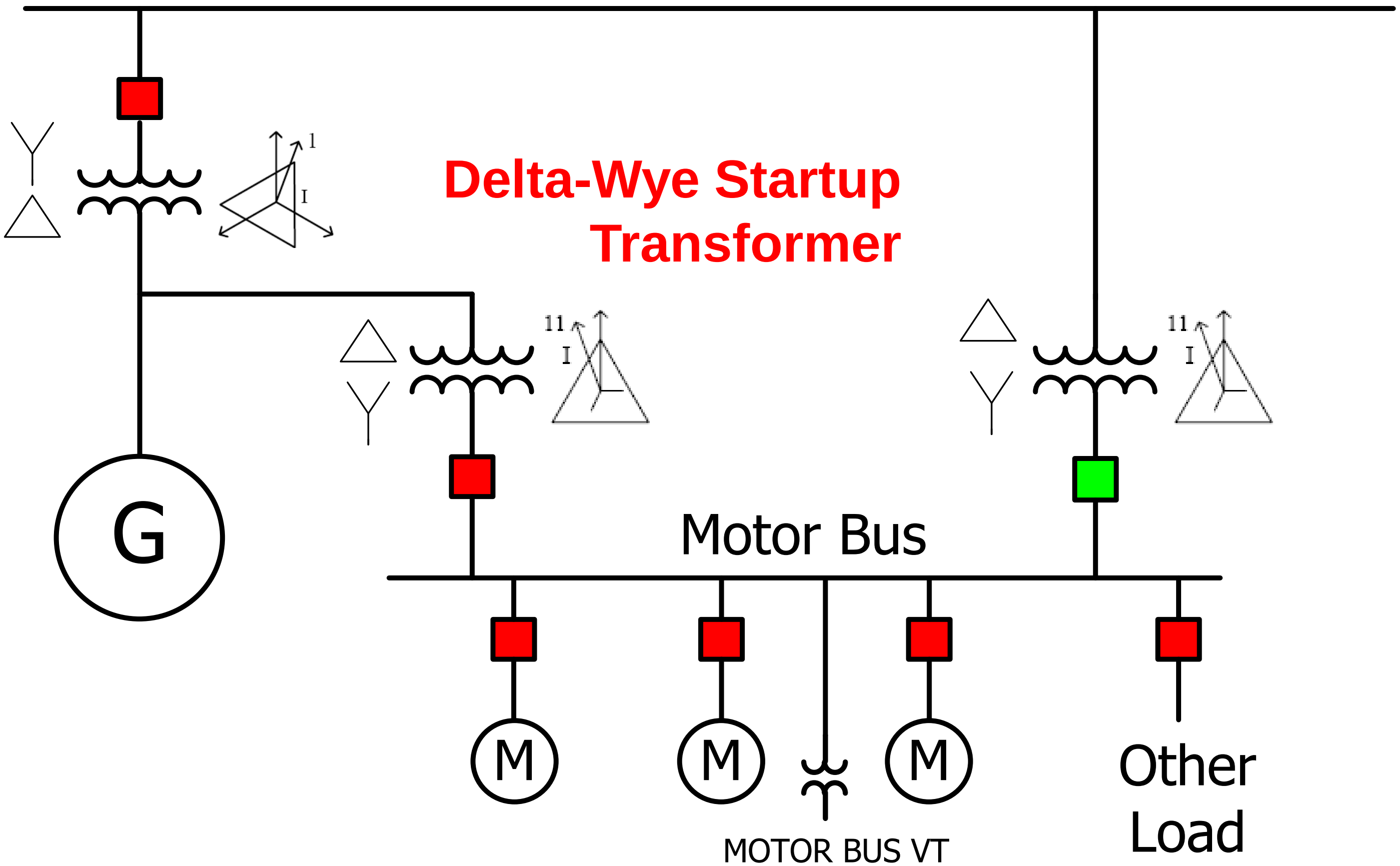
Unit-Connected Generator Motor Bus

- 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

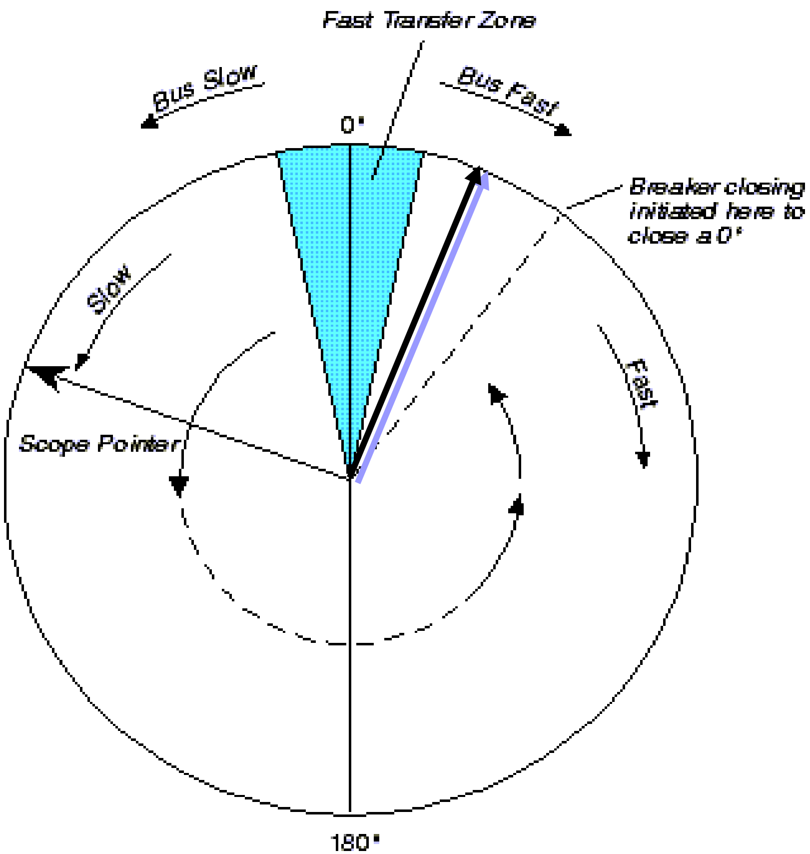
- In some plants, a delta-wye Startup Transformer has been specified, creating a 30° phase shift between the Unit Auxiliary and Startup Transformers.



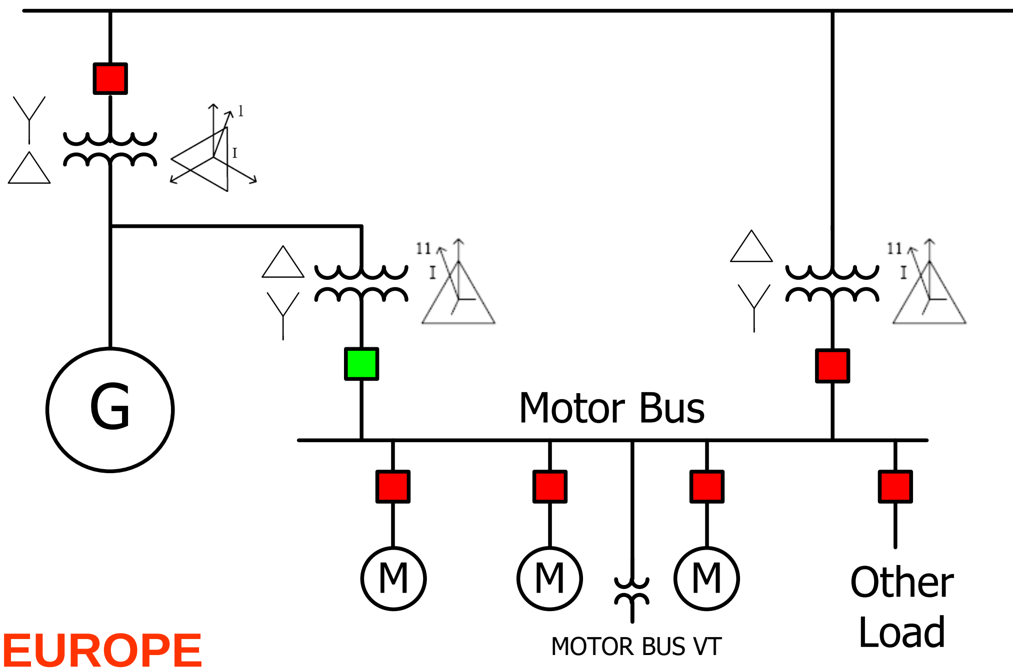
Unit-Connected Generator Motor Bus

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 slowing which moves the Bus voltage towards the Unit Aux Transformer voltage.

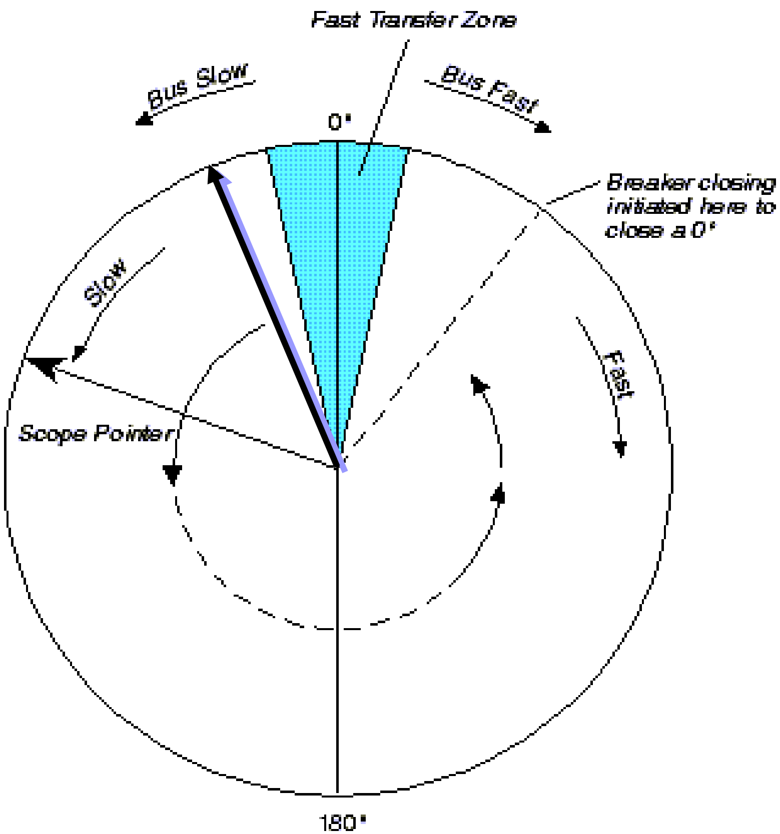


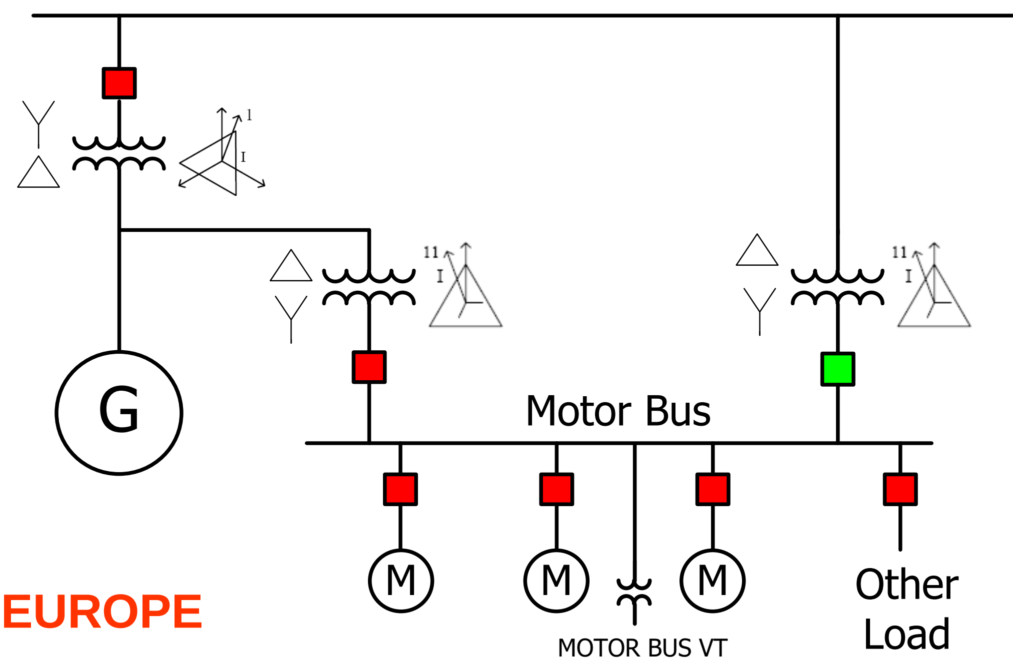
Unit-Connected Generator Motor Bus

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 slowing which moves the Bus voltage away from the Startup Transformer voltage.





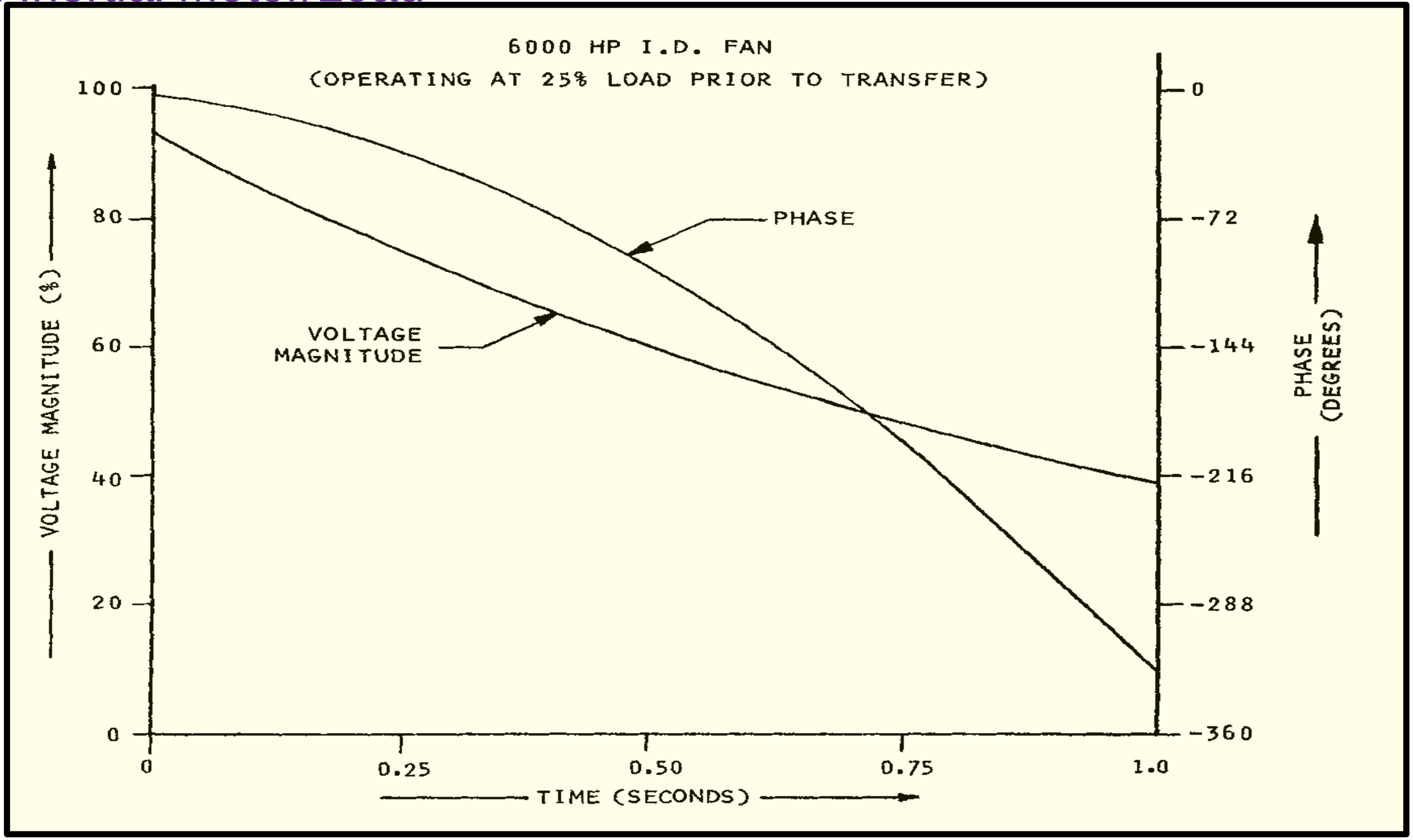
Transient Effects upon Disconnect of Motor Loads

- 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

Motor Bus Transfer

Phase Angle and Motor Bus Voltage Characteristics

High Inertial Motor/Load

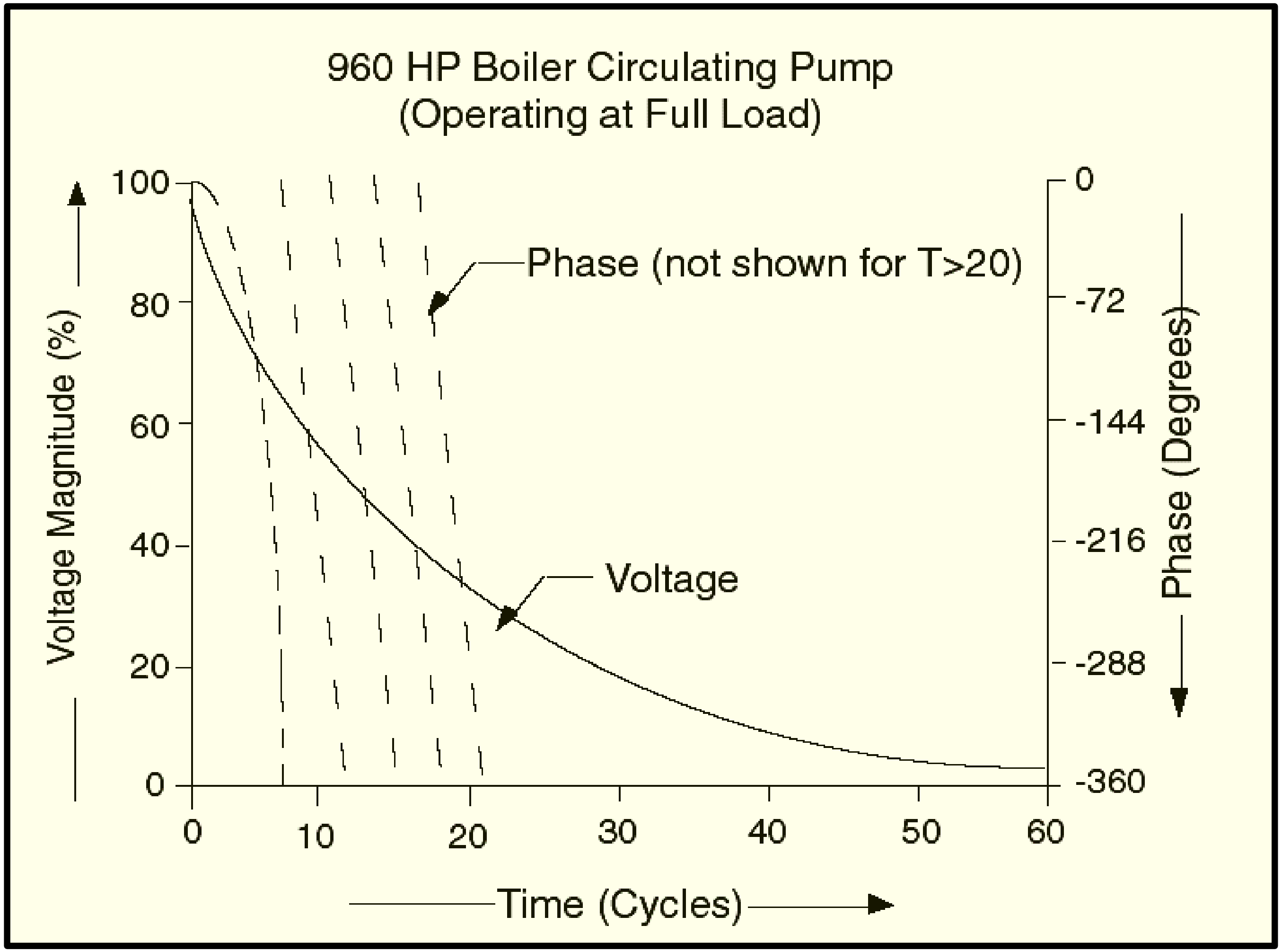


Phase angle rate of change (caused by deceleration of the motors during transfer) and the rate of voltage decay determined by the type of motors in use and the type of loads being driven.

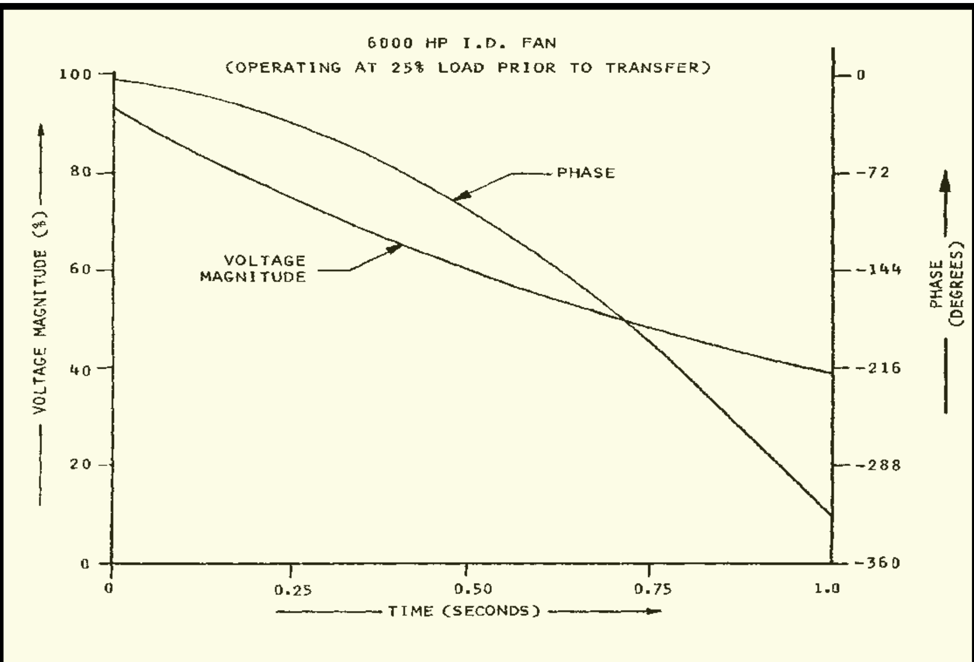
Motor Bus Transfer

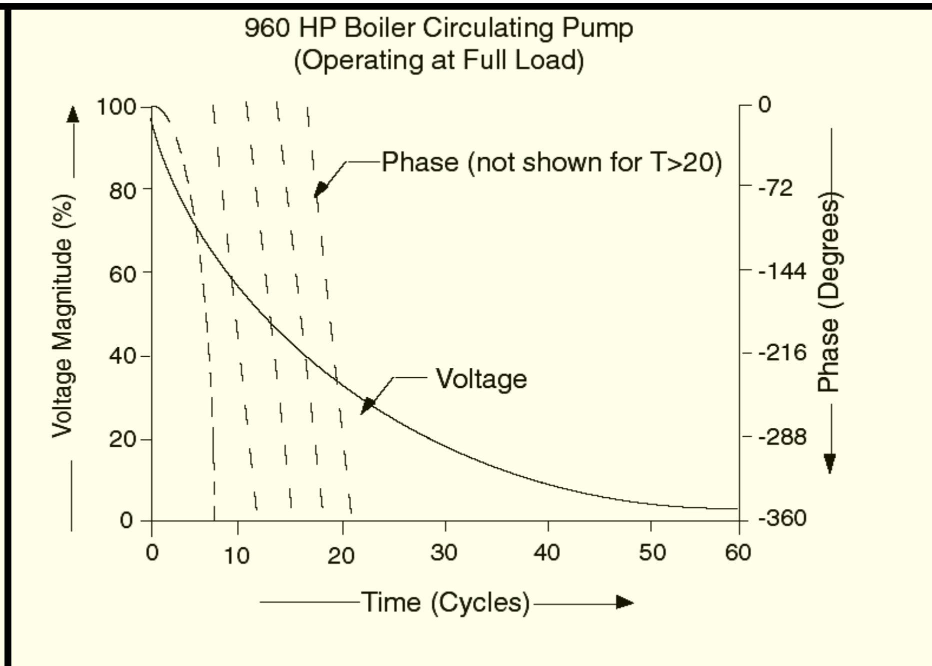
Phase Angle and Motor Bus Voltage Characteristics

Low Inertial Motor/Load



Effect of Motor/Load Inertia





- High inertial loads tend to hold up motor buses
- Motors on a bus create a composite decay characteristic

Transfer Initiate

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

- **<u>Protective Relay Initiate must come from ALL relay operations that would remove power from motor bus sources.</u>**

- External Initiate

- Auto Transfer Initiate on Bus Undervoltage
  When enabled, this automatically initiates transfer whenever the motor bus voltage drops below an undervoltage 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

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 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

MBT Performance Test Protocols

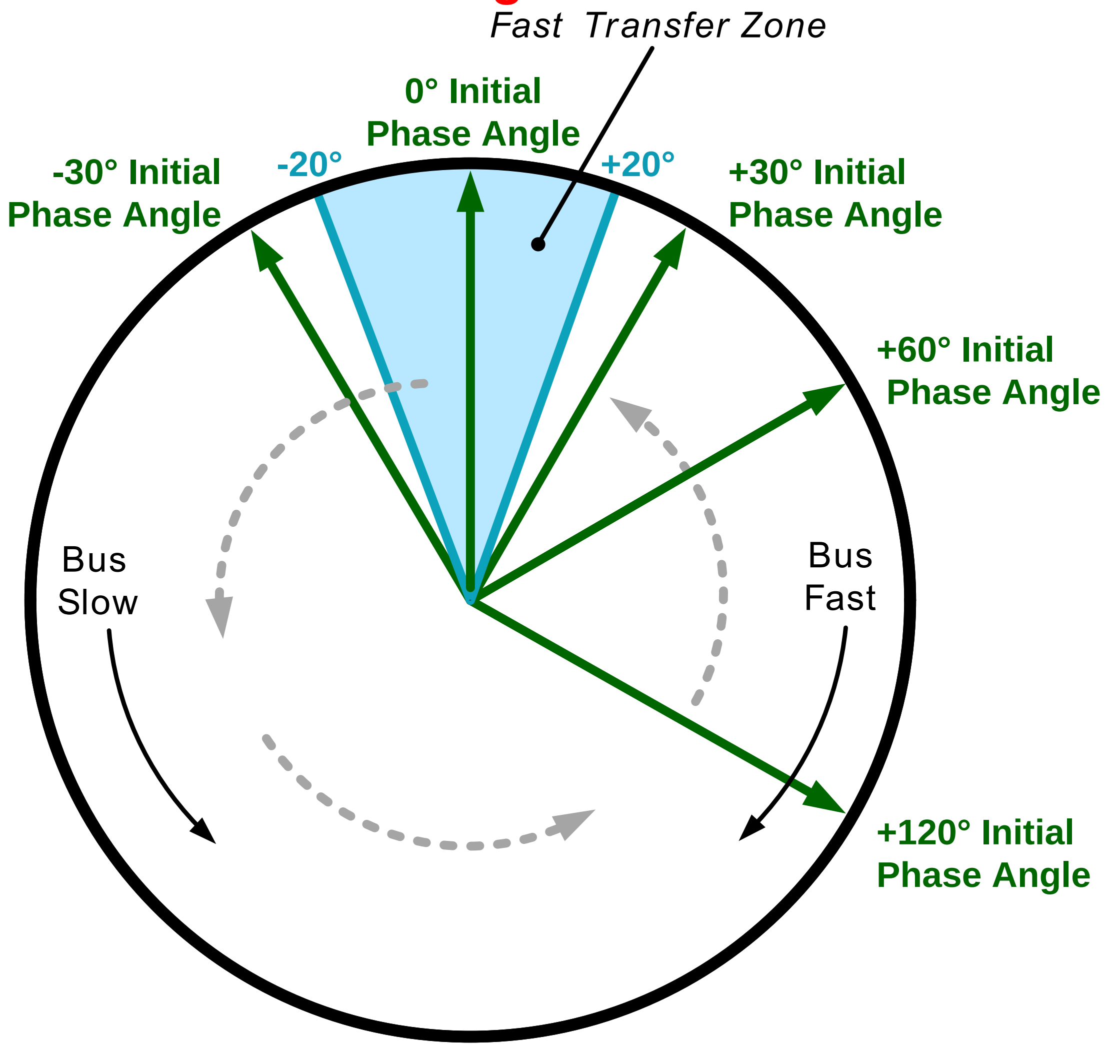
- The electric power industry presently has no industry standards on the performance requirements for relays used to supervise critical process motor bus transfers.
- A device-testing protocol was proposed in the 2012 IEEE Power System Relaying Committee Report for sync check relays used to implement 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.

Performance Verification Test

- Prove applicability of devices considered for use in supervising wide range of motor bus transfer characteristics on various plant buses.
- All protective relays applied must pass stringent performance standards before deemed safe for use in the field. The field is too late to get an ugly surprise that under real conditions, they don’t perform.
- A protective relay test set provides automated, consistent test conditions, replicating the wide range of aggregate motor sizes, inertia, and loads found in power plants and industrial facilities.
- The injected voltage and frequency decay rates, identified in Table I, represent the aggregate spindown characteristics of the motors on the bus after the Old Breaker is tripped.
- These Voltage and Frequency Decay rates cover the range from large medium voltage motors with high inertia loads to smaller low voltage motors with lower inertia loads.

MBT Extended Test Protocol

Dynamic Test of Motor Bus Transfer System – Initial Static Phase Angles



Prior conditions suggest that the new test protocol should include a variety of initial start angles before transfer initiate at each level of aggregate motor bus inertia.

MBT Test Protocol - Results

MBT TEST RESULTS

	TEST	Initial Ø Angle	Voltage Decay	Frequency Decay	Transfer Mode	Transfer Method	Advance Ø Angle	Close Ø Angle	Close ΔF	Close Volts	ANSI C50.41 pu V/Hz	Open Transfer Time cycles
HIGH INERTIA	1	-30	75 V/sec	8.33 Hz/sec	Sequential	IN-PHASE	25.8	0.7	-3.87	85.3	0.24	27.0
	2	+120	75 V/sec	8.33 Hz/sec	Sequential	IN-PHASE	15.5	-0.1	-2.24	99.9	0.14	15.2
	3	+60	75 V/sec	8.33 Hz/sec	Sequential	FAST	16.5	7.0	-1.46	106.9	0.15	9.8
	4	+30	75 V/sec	8.33 Hz/sec	Sequential	FAST	19.3	12.6	-0.70	112.3	0.22	5.0
	5	0	75 V/sec	8.33 Hz/sec	Sequential	FAST	-1.3	-4.0	-0.27	116.6	0.08	1.7
MEDIUM INERTIA	6	-30	94 V/sec	20 Hz/sec	Sequential	IN-PHASE	40.7	1.7	-5.76	93.3	0.15	16.7
	7	+120	94 V/sec	20 Hz/sec	Sequential	IN-PHASE	28.1	6.5	-3.24	105.0	0.09	9.5
	8	+60	94 V/sec	20 Hz/sec	Sequential	IN-PHASE	18.9	-1.7	-2.19	108.3	0.07	6.2
	9	+30	94 V/sec	20 Hz/sec	Sequential	FAST	18.3	5.7	-1.21	112.8	0.09	3.5
	10	0	94 V/sec	20 Hz/sec	Sequential	FAST	-4.6	-10.9	-0.68	116.3	0.20	1.8
LOW INERTIA	11	-30	104 V/sec	31 Hz/sec	Sequential	IN-PHASE	59.5	11.9	-6.96	97.1	0.15	13.3
	12	+120	104 V/sec	31 Hz/sec	Sequential	IN-PHASE	30.4	2.9	-3.79	105.7	0.06	7.3
	13	+60	104 V/sec	31 Hz/sec	Sequential	IN-PHASE	22.1	-2.1	-2.86	110.6	0.07	5.0
	14	+30	104 V/sec	31 Hz/sec	Sequential	FAST	17.8	1.7	-1.56	113.2	0.04	2.8
	15	0	104 V/sec	31 Hz/sec	Sequential	FAST	-5.7	-13.4	-0.84	115.5	0.26	1.5

ANSI/NEMA STANDARD C50.41-2012

Polyphase Induction Motors for Power Generating Stations

A fast transfer or reclosing is defined as one which:

a) occurs within a time period of 10 cycles or less,

b) the maximum phase angle between the motor residual volts per hertz vector and the system equivalent volts per hertz vector does not exceed 90 degrees, and

c) the resultant volts per hertz between the motor residual volts per hertz phasor and the incoming source volts per hertz phasor at the instant of transfer or reclosing is completed does not exceed 1.33 per unit volts per Hz on the motor rated voltage and frequency basis.

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.

MBT Test Protocol - Results

- **Test voltage and frequency decay characteristics of High, Medium, and Low Inertia Motor Buses**
- **Tests with Multiple Initial Static Phase Angles**
- **All 15 tests closed under 0.26 pu V/Hz**.
- **All 15 tests closed well below the 1.33 pu V/Hz and 90 degree limits***

***** ANSI/NEMA C50.41 Polyphase Induction Motors for Power Generating Stations

- **All 15 tests were performed with NO changes to settings**.
  - ✓ **Fast Transfer Method Phase Angle Limit = 20°**
  - ✓ **Fast Transfer Method Slip Frequency Limit = 2.0 Hz ****
  - ✓ **In-Phase Transfer Method Slip Frequency Limit = 10.0 Hz**

****** Used to coordinate the actions of the Fast Transfer and the In-Phase Transfer Methods to achieve an optimal close with the In-Phase Transfer Method.

MBT Test Protocol - Observations

- **The ANSI/NEMA C50.41 "10 cycles or less" criteria would reject perfectly good transfers by the In-Phase Transfer Method:**
  - ✓ **A High Inertia close at 0.24 pu V/Hz took 27 cycles**
  - ✓ **A Medium Inertia close at 0.15 pu V/Hz took 16.7 cycles**
  - ✓ **A Low Inertia close at 0.15 pu V/Hz took 13.3 cycles**
- **The arbitrary 10-cycle limit must be ignored as it may take more than 10 cycles for the motors to rotate back into synchronism.**
- **How fast can the motors transfer?**
  When the motors allow it by rotating back into sync ! ! !
- **In the fast-moving world of motor bus transfer:**
  - ✓ **10 cycles (167 ms) is an eternity**
  - ✓ **10 cycles never was a safe limit for fast transfer***

***** Even at a **medium** frequency decay of **20 Hz/sec** (R_S), with zero initial slip frequency (S_{INIT}), the angle movement ($\Delta Ø$) **in 10 cycles** (T) is a dangerous **100°** .

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

MBT Test Protocol - Observations

- Synchronous Fast and In-Phase Transfers occur well before the 0.25 pu voltage level of the Residual Voltage Slow Transfer would operate.
- Synchronous Transfers vs. blind Residual Voltage Transfers:
  - ✓ Much higher voltages
  - ✓ Much lower slip frequencies
  - ✓ With synchronous closure
- Residual Voltage Transfers can subject motors and loads to:
  - ✓ The jarring effect of a large phase angle at breaker closure
  - ✓ High inrush current and associated torque
  - ✓ Lengthy undervoltage causing motor trip or dropout
  - ✓ Load shed if the new source cannot reaccelerate all the motors simultaneously
  - ✓ Load shed if transfer would cause excessive plant voltage dip
- Results at Low Inertia demonstrate that the Fast and In-Phase Methods, can also be applied to Low Voltage Motor Buses, rather than having to resort to Residual Voltage Slow Transfers.

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**):

$$T = P_{AG}/\omega_S$$

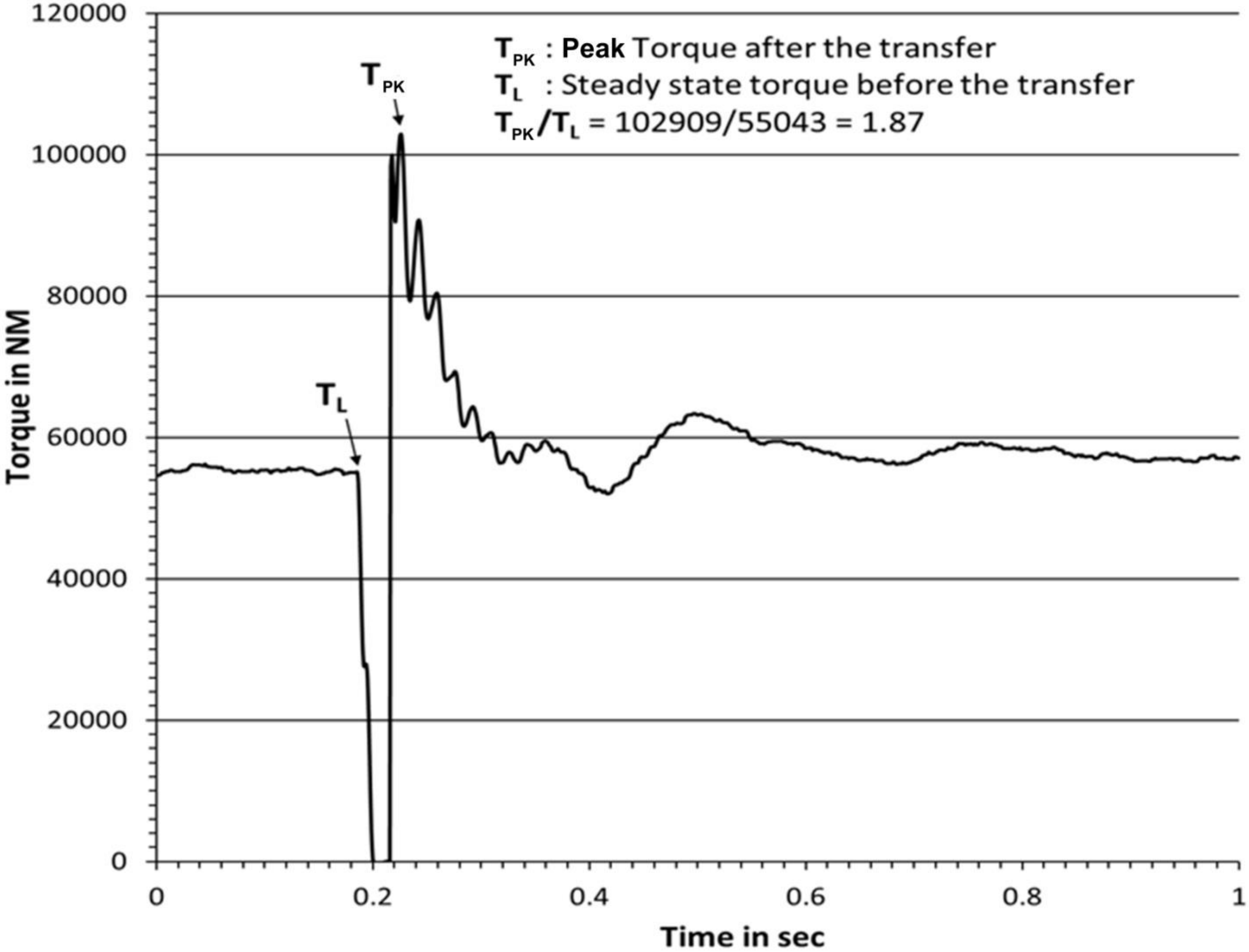
Assumes all losses (copper, iron, friction, and windage losses) are neglected.

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 Before and After Transfer



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

On-Site Live MBT Field Results

Live Open Transition Transfers Under Normal Operating Load Conditions

MBT FIELD RESULTS VS = 120 FS = 60

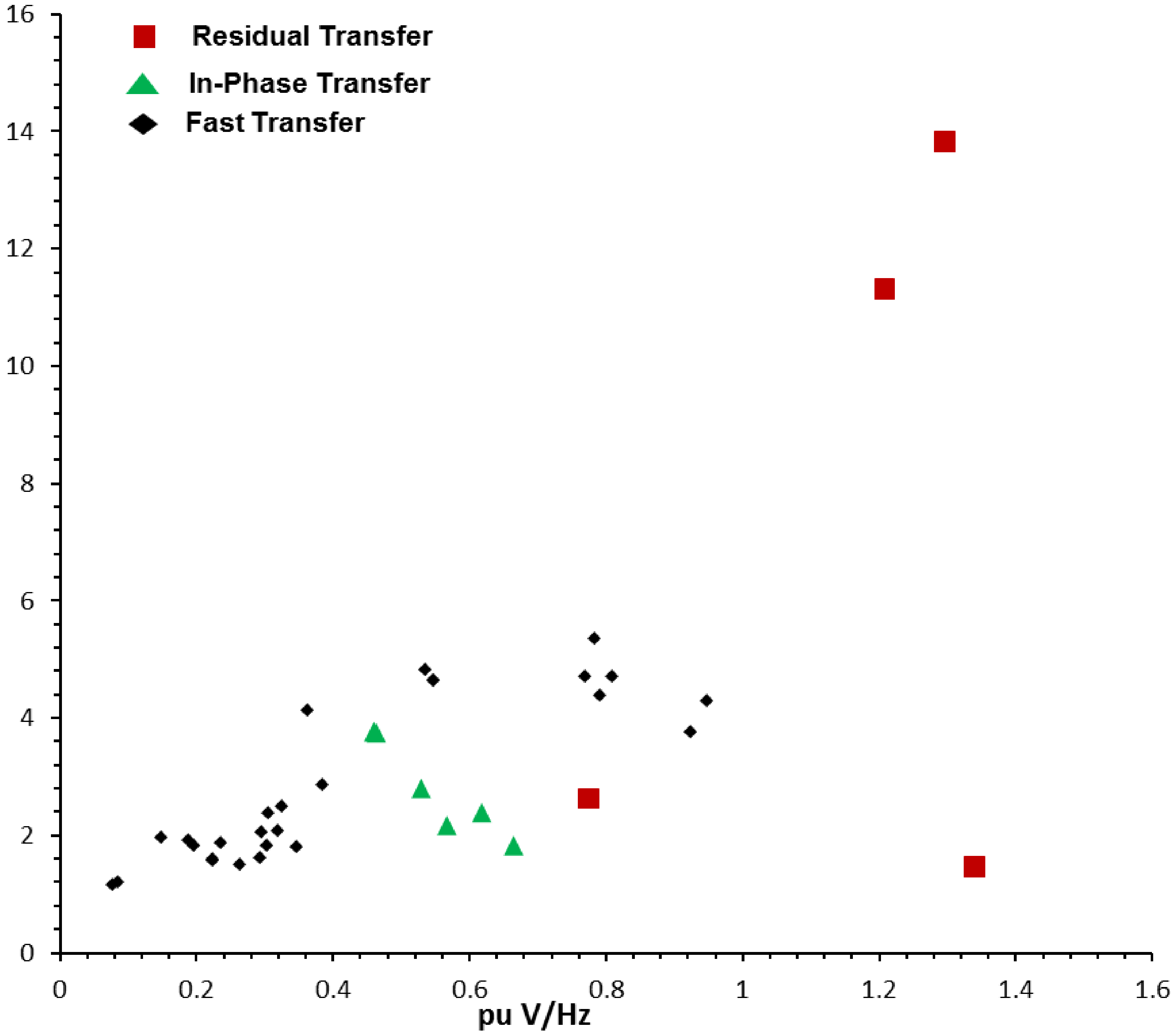
LOCATION	Transfer Mode	Transfer Method	Advance Ø Angle	Close Ø Angle	Close ΔF	Close Volts	ANSI C50.41 pu V/Hz	Open Transfer Time cycles	Torque Ratio T_{PK}/T_{L}
FACILITY 19	Sequential	FAST	-32.4	-47.3	-0.73	107.2	0.7689	3.3	4.70
FACILITY 20	Sequential	FAST	24.4	9.5	-0.36	106.6	0.1892	3.3	1.91
FACILITY 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 Ratios (T_{PK}/T_L) vs. pu V/Hz

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 (T_{PK}/T_L) vs. pu V/Hz



Residual Voltage Transfer Results

- **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, well below the open-circuit AC time constant value, approaching the alleged "safe" zone.**

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

Excerpts from ANSI/NEMA C50.41-2012

14 Bus Transfer or Reclosing

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.

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.**

1.5 times the open-circuit machine time constant: The time for self-generated voltage to decay to 22.3% of rated bus voltage or 26.8 Vac on a 120 Vac PT secondary. **That is NOT low enough! BUT any lower and the motors drop off.**

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

Detailed Observations and Analysis

FACILITIES 18 THROUGH 27

CHALLENGE

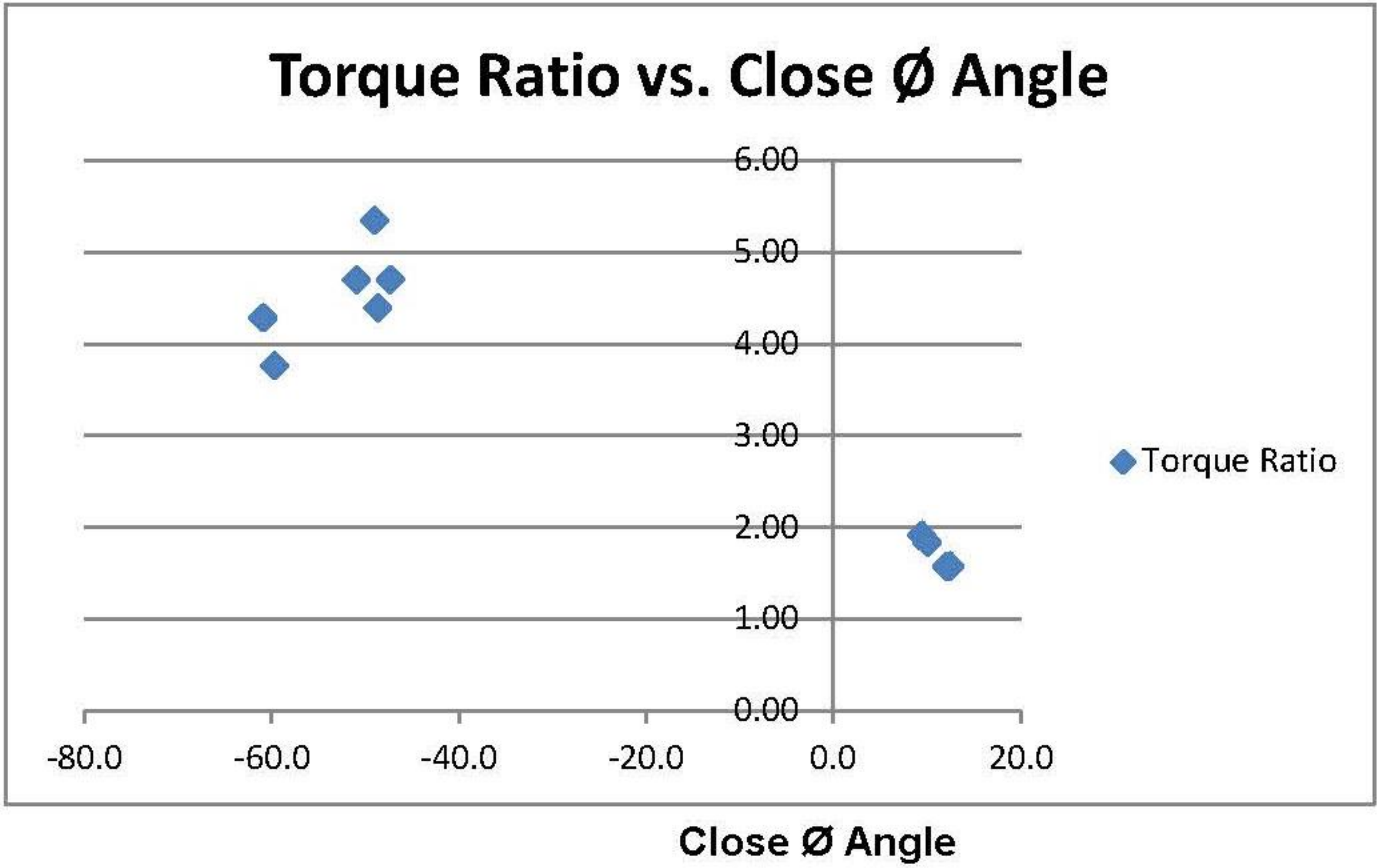
- Initial 30° Phase Shift Mismatch Between Source Transformers
- Must use Sequential vs. Simultaneous mode transfer as can't risk a breaker failure that would even momentarily parallel the two out-of-phase transformers
- Low Inertia, rapidly decaying nature of the motors on the bus, precludes the use of In-Phase Transfer when the Initial Angle is -30° as motors would drop out on low voltage.

SOLUTION

- Set Fast Transfer Phase Angle Limit to 40° so transfer can be initiated immediately with the initial angle of -30° .
- Transfers starting at +30° close at smaller angles (9.5° to 12.5°) and Torque Ratios (1.57 to 1.91), and those starting at -30° and moving away from zero degrees close at larger angles (-47.3 to -60.9) and Torque Ratios (3.76 to 5.34).

Detailed Observations and Analysis

FACILITY	18	19	20	21	22	23	24	25	26	27
Close ø Angle	-48.6	-47.3	9.5	-50.9	12.5	12.1	-59.7	10.1	-60.9	-49.0
Torque Ratio	4.39	4.70	1.91	4.70	1.58	1.57	3.76	1.83	4.28	5.34



FACILITY 10

CHALLENGE

- **Initial Static Phase Angle $Ø_{INIT} = 115°$ preventing any immediate attempt to perform a Fast Transfer.**

SOLUTION

- **The In-Phase Method of Transfer provided a successful synchronous transfer opportunity, closing at 0.6178 pu V/Hz with a Torque Ratio of 2.39.**
- **The breaker close command was sent at an Advance Ø Angle of 55° before zero, and at a bus voltage well above the Residual Voltage Transfer setpoint.**

Detailed Observations and Analysis

FACILITY 1
NEED FOR SIMULTANEOUS TRANSFER MODE

- **Simultaneous Mode Fast Transfers shorten Open Transfer Times to ensure transfer in cases of very low motor bus inertia.**
- **Observations - Simultaneous Mode Fast Transfer**
  - ✓ **Open Transfer Time of only 1.3 cycles**
  - ✓ **Phase Angle moved 19.9°**
  - ✓ **Slip Frequency increased by 2.83 Hz**
  - ✓ **Bus Voltage dropped to 93.8 volts**
  - ✓ **Closing at 0.36 pu V/Hz with a Torque Ratio of 4.12**
- **With motors and loads that are dragging down the frequency so rapidly, this is definitely a case for Simultaneous Mode Fast Transfer.**
- **Keep in mind that a Breaker Failure scheme is mandatory for the Simultaneous Mode of Transfer in case the old breaker fails to trip.**

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.**

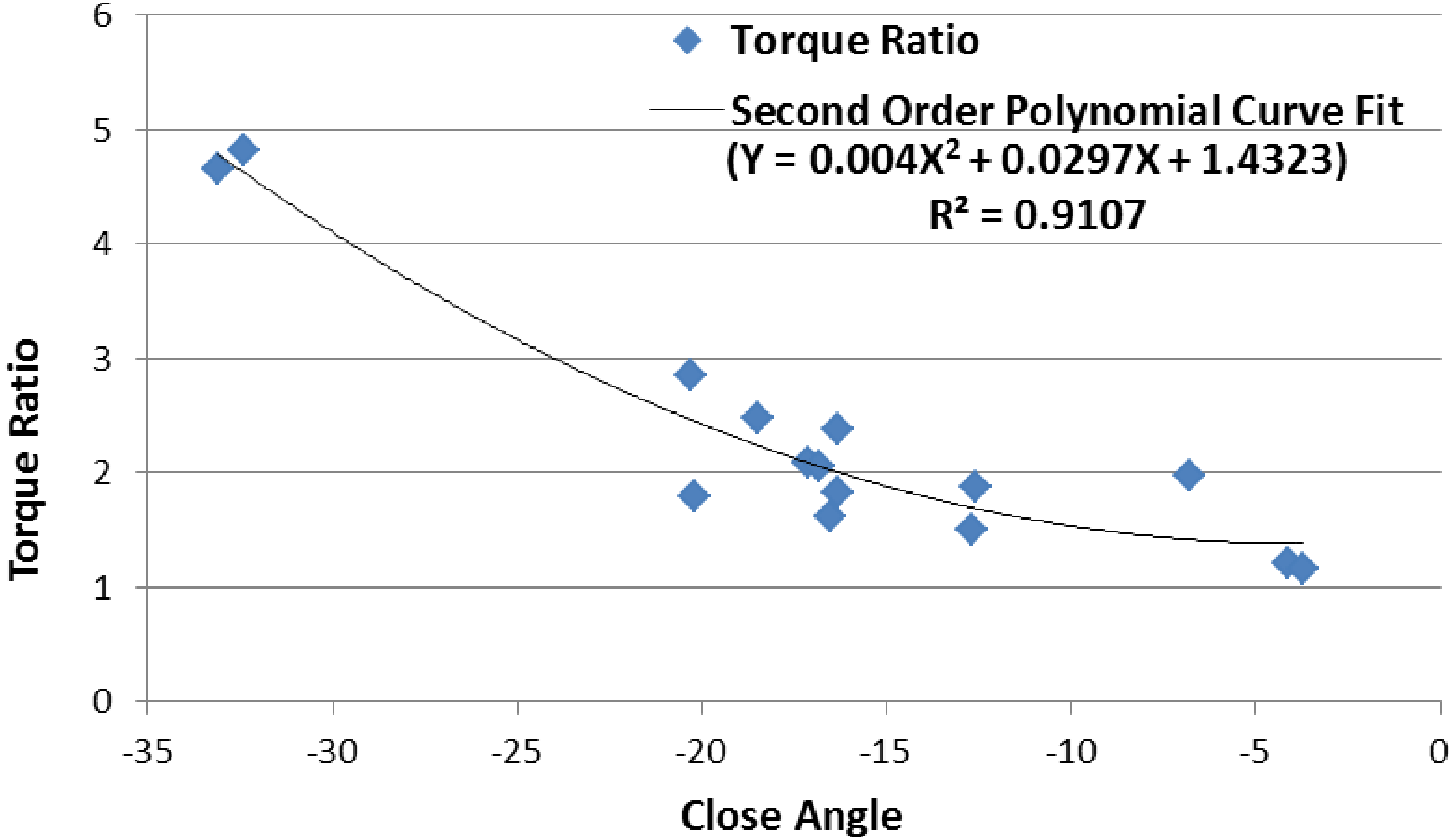
FACILITY 11 In-Phase	FACILITY 16 In-Phase	FACILITY 17 In-Phase
37.7 Vac	62.7 Vac	62.2 Vac
-4.48 Hz	-2.07 Hz	-2.07 Hz
7.1°	2.2°	-1.1°
Transfer=17.7 cycles	Transfer=50.0 cycles	Transfer=50.6 cycles
0.0644 pu V/Hz	0.4597 pu V/Hz	0.4634 pu V/Hz
Torque Ratio=1.89	Torque Ratio=3.77	Torque Ratio=3.75

Fast Transfer Study of Correlation Between Torque Ratio and Close Angle

- To determine the relationship between the Torque Ratio and the Phase Angle at Close, these results from Fast Transfers at Facilities 2-8, 12-15, 28-29, 33 and 34 are plotted.
- A regression analysis goodness-of-fit statistical measure R^2 (coefficient of determination) is used with different curve fitting equations to ascertain the relationship.
- A second order polynomial with an R^2 of 0.9107 gave the best fit, compared with linear (R^2 of 0.7988) and exponential (R^2 of 0.8226) curves.
- The Torque Ratio increases with the increase in Close Angle, and the increase is more rapid at large Close Angles as indicated by the second order polynomial curve defined by the equation $Y = 0.004X^2 + 0.0297X + 1.4323$

Detailed Observations and Analysis

Fast Transfer Study of Correlation Between Torque Ratio and Close Angle



Motor Torque Ratio T_{PK}/T_L Conclusions

- **Although the Fast Transfer Torque Ratios from these Facilities are relatively low, with transfers at Close Angles of 33° or less, the graph of Torque Ratio vs. Close Angle shows a second order polynomial trend indicating that the torque resulting from significantly out-of-phase bus transfers may be severe.**
- **This excellent fit between the Torque Ratio metric and Close Angle for 15 motor bus transfers, regardless of Close Voltage and Frequency Difference, performed at 15 different facilities, with different motor bus characteristics around the world, would also seem to greatly reinforce the value of the Torque Ratio metric.**
- **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

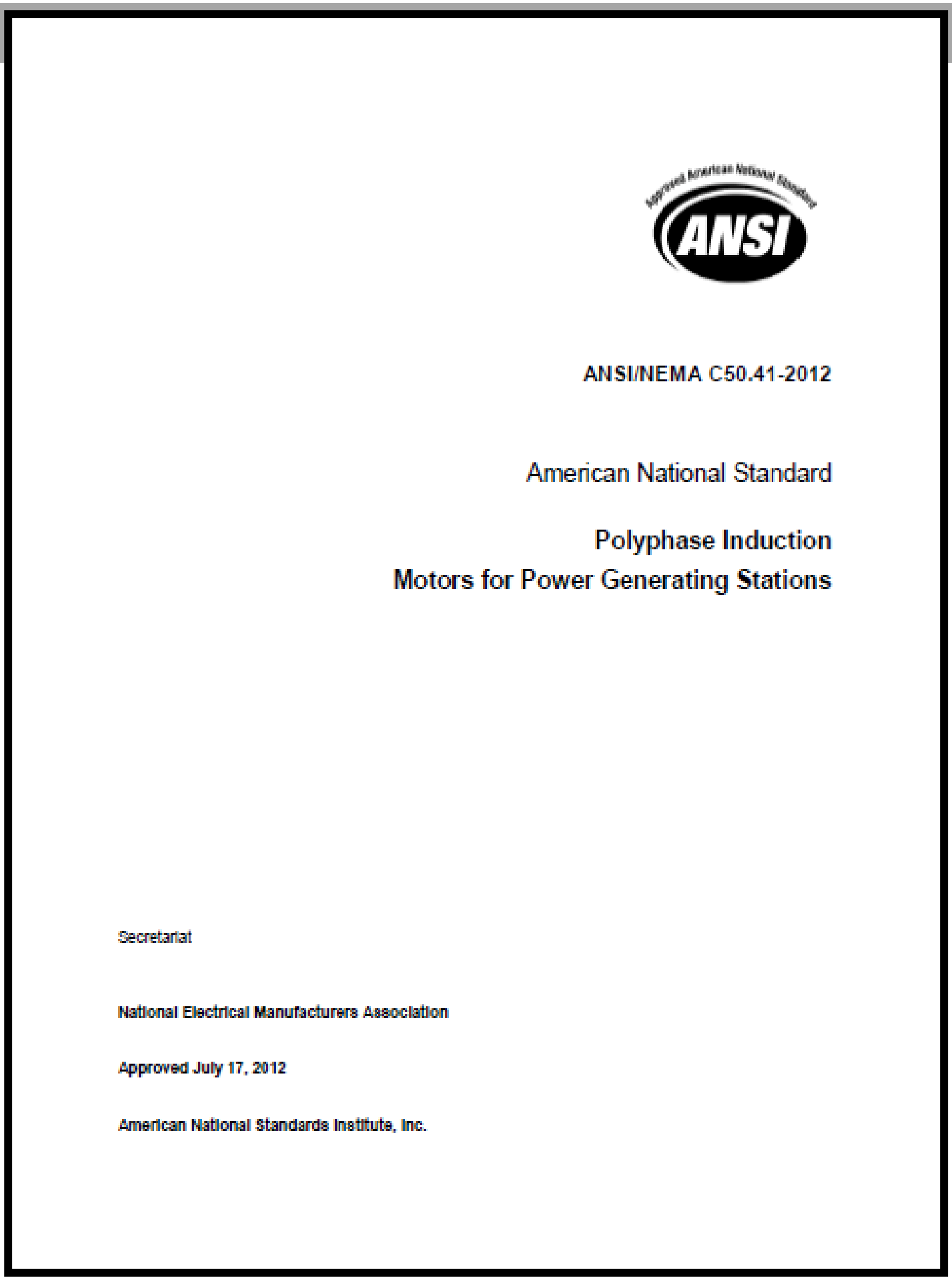
- Normal Across-the-Line Motor Start
- Three-Phase Fault on the Motor
- In-Phase Transfer
- Residual Voltage Transfer,
  Closing at Various Phase Angles

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.

Motor Modeling



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

Polyphase Induction Motors for Power Generating Stations

ANSI/NEMA STANDARD C50.41-2012

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**
- **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

14.2 Slow Transfer or Reclosing

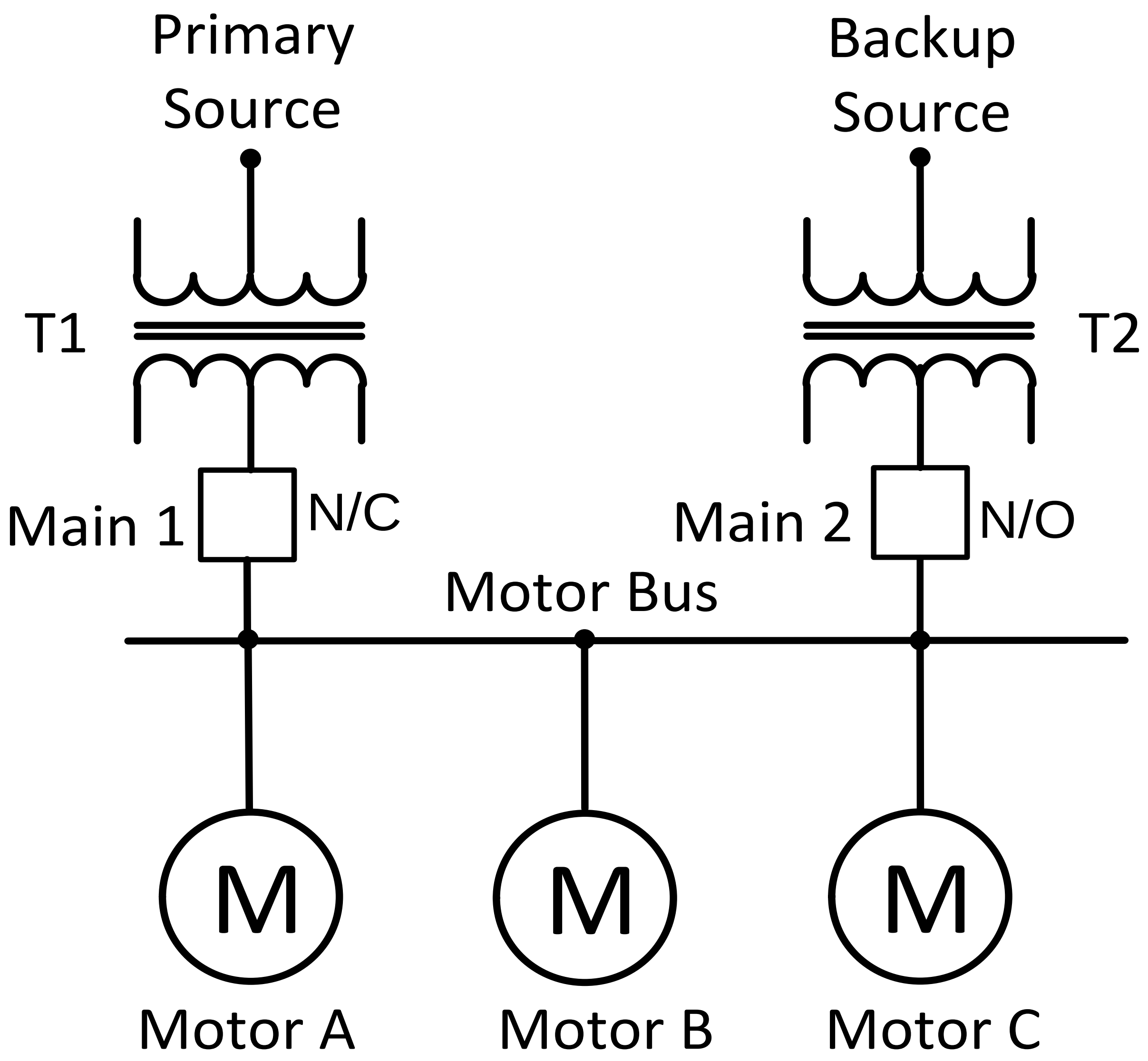
- **To limit possibility of damaging the motor or driven equipment**... the resultant volts per hertz **at transfer doesn't exceed 1.33 pu V/Hz**
- **Delayed until motor rotor flux linkages decayed**… accomplished by a time delay equal or greater than **1.5 times the open-circuit AC time constant of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

ANSI/NEMA STANDARD C50.41-2012

14.3 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**

The Motor Bus



The Motor Bus

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%

Motor Modeling

IEEE STANDARDS ASSOCIATION   IEEE

IEEE Guide for AC Motor Protection

IEEE Power and Energy Society

Sponsored by the
Power System Relaying Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

20 February 2013

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

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

IEEE Std C37.96-2012 Definitions

In-Phase Transfer: “An open-transition method wherein the close command to the new breaker occurs at a phase angle in advance of phase coincidence between the motor bus and the new source to compensate for the new breaker's closing time”

Residual Voltage Transfer: “An open-transition method wherein the voltage magnitude at the motor bus falls below a predetermined level before the close command is issued to the new breaker. There is no supervision of the synchronous condition between the motor bus and the new source”

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

IEEE Std C37.96-2012, Clause 6.4.8-13

- Events that occur or conditions that exist immediately prior to opening the initial source breaker
- Faults on the initial source
- Condition of the alternative source
- Effects of an out-of-step (OOS) generator trip
- System separation between incoming supply sources
  - Different supply voltages
  - Abnormal system operation
  - Loading of the supply transformers
- Supply source transformer winding phase shift
- Transient effects upon disconnection of motor loads

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!

Round and round she goes, and where she stops, nobody knows!

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

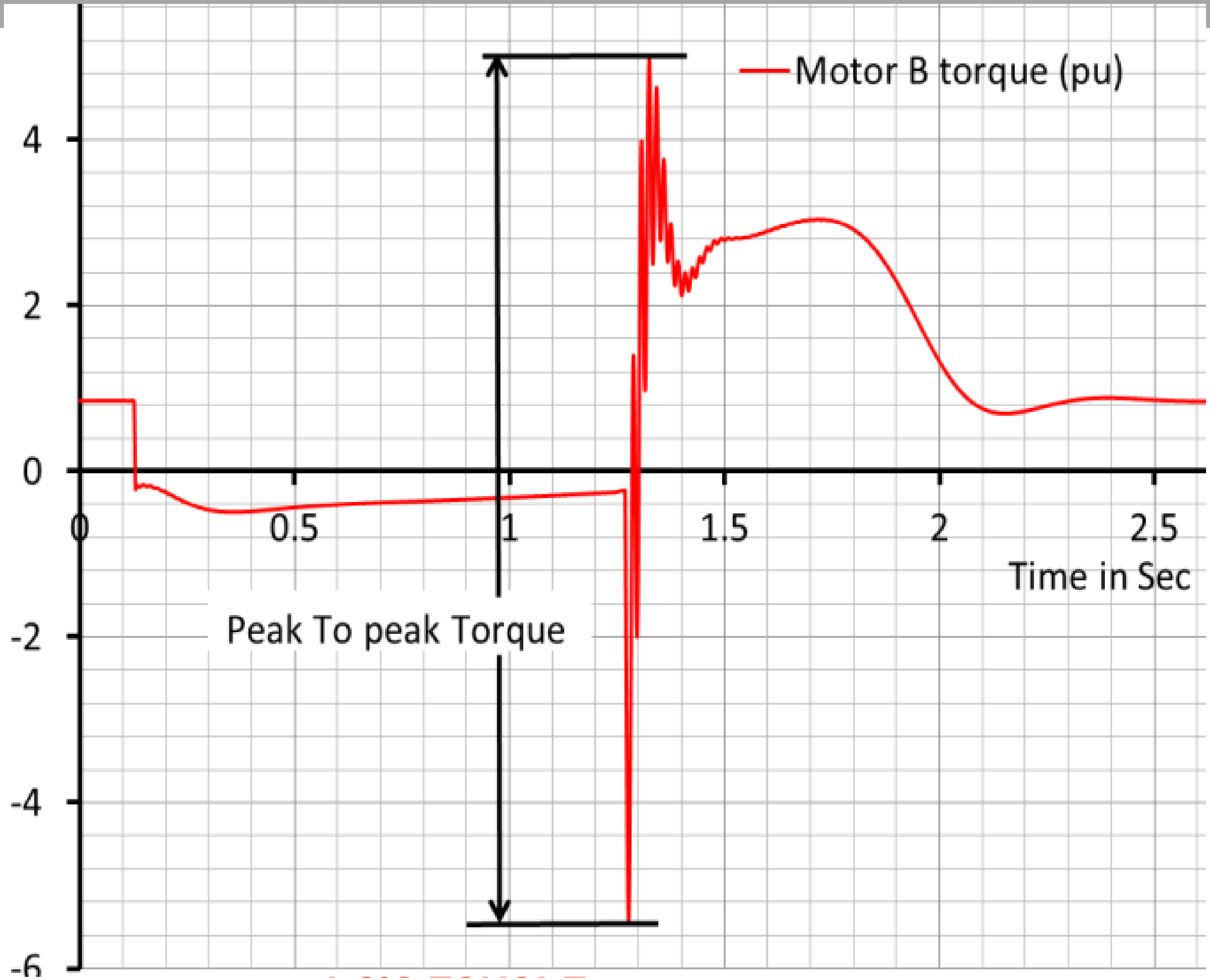
- **Normal Across-the-Line Motor Start -** Induction motors experience high stator current and torque during motor start, and are designed to sustain this condition for short periods of time. The model includes starting parameters: locked rotor current and breakdown torque.
- **Three-Phase Short Circuit 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



Test Results - Transient Currents & Torques during Residual Voltage MBT

RESIDUAL VOLTAGE TRANSFER VS. MOTOR START AND IN-PHASE TRANSFER (Gray>Normal Start)

Closing Angle	1.34	32.55	62.55	92.55	122.73	153.09	183.45	210.41	240.41	270.41	300.61	330.97	**Normal Start**	**In-Phase Transfer**
Motor A Peak Current	**6.90**	**5.55**	**5.22**	**5.36**	**5.46**	**6.44**	**7.44**	**8.54**	**8.59**	**9.05**	**8.69**	**7.63**	**4.70**	**3.44**
Motor B Peak Current	**9.94**	**7.96**	**7.05**	**7.60**	**8.98**	**10.68**	**12.28**	**13.73**	**13.49**	**13.98**	**13.07**	**11.26**	**6.28**	**4.54**
Motor C Peak Current	**9.00**	**7.37**	**6.39**	**6.28**	**6.81**	**8.02**	**9.27**	**10.62**	**10.74**	**11.44**	**11.05**	**9.88**	**5.85**	**3.88**
Motor A NegativePeak Torque	0.00	0.00	0.00	-0.87	-2.06	-3.09	-3.65	-3.56	-2.88	-1.88	-0.88	-0.17	0.00	0.00
Motor B NegativePeak Torque	-0.49	-0.49	-0.94	-2.43	-4.04	-5.17	-5.43	-4.74	-3.40	-1.93	-0.78	-0.49	0.00	-0.49
Motor C NegativePeak Torque	-0.10	-0.10	-0.10	-0.53	-2.09	-3.60	-4.57	-4.74	-4.06	-2.80	-1.41	-0.33	0.00	-0.10
Motor A PositivePeak Torque	2.27	2.47	2.72	3.08	3.27	3.42	3.48	3.28	2.82	2.51	2.06	1.79	1.80	2.95
Motor B PositivePeak Torque	3.76	4.22	4.47	4.66	4.94	5.03	4.87	4.54	4.26	3.87	3.51	3.30	3.24	4.04
Motor C PositivePeak Torque	2.57	2.80	3.14	3.55	3.82	3.85	3.76	3.65	3.32	2.82	2.51	2.29	2.25	3.36
Motor A Transient Pk-to-Pk Torque	**2.27**	**2.47**	**2.72**	**3.95**	**5.33**	**6.52**	**7.13**	**6.83**	**5.70**	**4.39**	**2.94**	**1.97**	**1.80**	**2.95**
Motor B Transient Pk-to-Pk Torque	**4.25**	**4.71**	**5.41**	**7.09**	**8.98**	**10.20**	**10.30**	**9.28**	**7.66**	**5.80**	**4.29**	**3.79**	**3.24**	**4.53**
Motor C Transient Pk-to-Pk Torque	**2.67**	**2.90**	**3.24**	**4.08**	**5.91**	**7.45**	**8.34**	**8.39**	**7.38**	**5.62**	**3.93**	**2.61**	**2.25**	**3.46**
Resultant pu V/Hz	**0.67**	**0.74**	**0.90**	**1.07**	**1.22**	**1.31**	**1.33**	**1.29**	**1.21**	**1.06**	**0.88**	**0.73**		**0.66**

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

- 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.

Comparison of Currents and Torques Residual Voltage Transfer vs. In-Phase Transfer and Motor Start (continued)

- For all motors, the peak currents for In-Phase Transfers are all lower than the Normal Start currents, and all much lower than currents for Residual Voltage Transfers.
- In 89% of the cases, the currents during Residual Voltage Transfer are in excess of six times rated current, which is typically the maximum specified for across-the-line motor starting.
- ALL Residual Voltage Transfers closing over six times rated torque are still given passing grades of 1.33 pu V/Hz or less.

Test Results - Transient Currents & Torques During Residual Voltage MBT

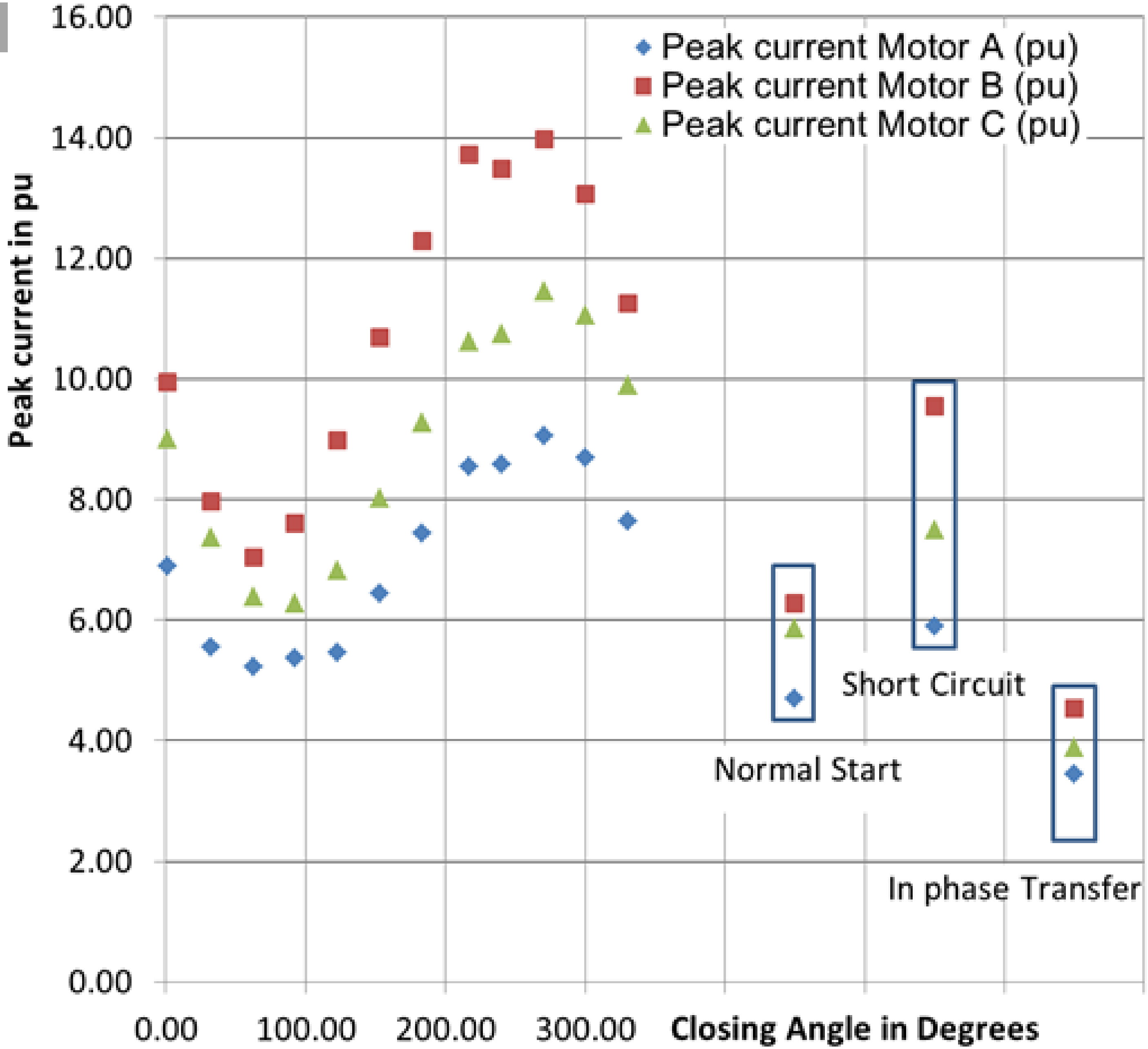
RESIDUAL VOLTAGE TRANSFER VS. MOTOR 3-Ø SHORT CIRCUIT
(Gray>Short Circuit)

Closing Angle	1.34	122.73	153.09	183.45	210.41	240.41	270.41	300.61	330.97	**Short Circuit**
Motor A Peak Current	**6.90**	5.46	**6.44**	**7.44**	**8.54**	**8.59**	**9.05**	**8.69**	**7.63**	**5.90**
Motor B Peak Current	**9.94**	8.98	**10.68**	**12.28**	**13.73**	**13.49**	**13.98**	**13.07**	**11.26**	**9.55**
Motor C Peak Current	**9.00**	6.81	**8.02**	**9.27**	**10.62**	**10.74**	**11.44**	**11.05**	**9.88**	**7.50**
Motor A NegativePeak Torque	0.00	-2.06	-3.09	-3.65	-3.56	-2.88	-1.88	-0.88	-0.17	-4.03
Motor B NegativePeak Torque	-0.49	-4.04	-5.17	-5.43	-4.74	-3.40	-1.93	-0.78	-0.49	-6.46
Motor C NegativePeak Torque	-0.10	-2.09	-3.60	-4.57	-4.74	-4.06	-2.80	-1.41	-0.33	-5.38
Motor A PositivePeak Torque	2.27	3.27	3.42	3.48	3.28	2.82	2.51	2.06	1.79	1.67
Motor B PositivePeak Torque	3.76	4.94	5.03	4.87	4.54	4.26	3.87	3.51	3.30	2.21
Motor C PositivePeak Torque	2.57	3.82	3.85	3.76	3.65	3.32	2.82	2.51	2.29	1.38
Motor A Transient Transfer Torque	2.27	5.33	**6.52**	**7.13**	**6.83**	**5.70**	4.39	2.94	1.97	**5.70**
Motor B Transient Transfer Torque	4.25	**8.98**	**10.20**	**10.30**	**9.28**	7.66	5.80	4.29	3.79	**8.68**
Motor C Transient Transfer Torque	2.67	5.91	**7.45**	**8.34**	**8.39**	**7.38**	5.62	3.93	2.61	**6.76**

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

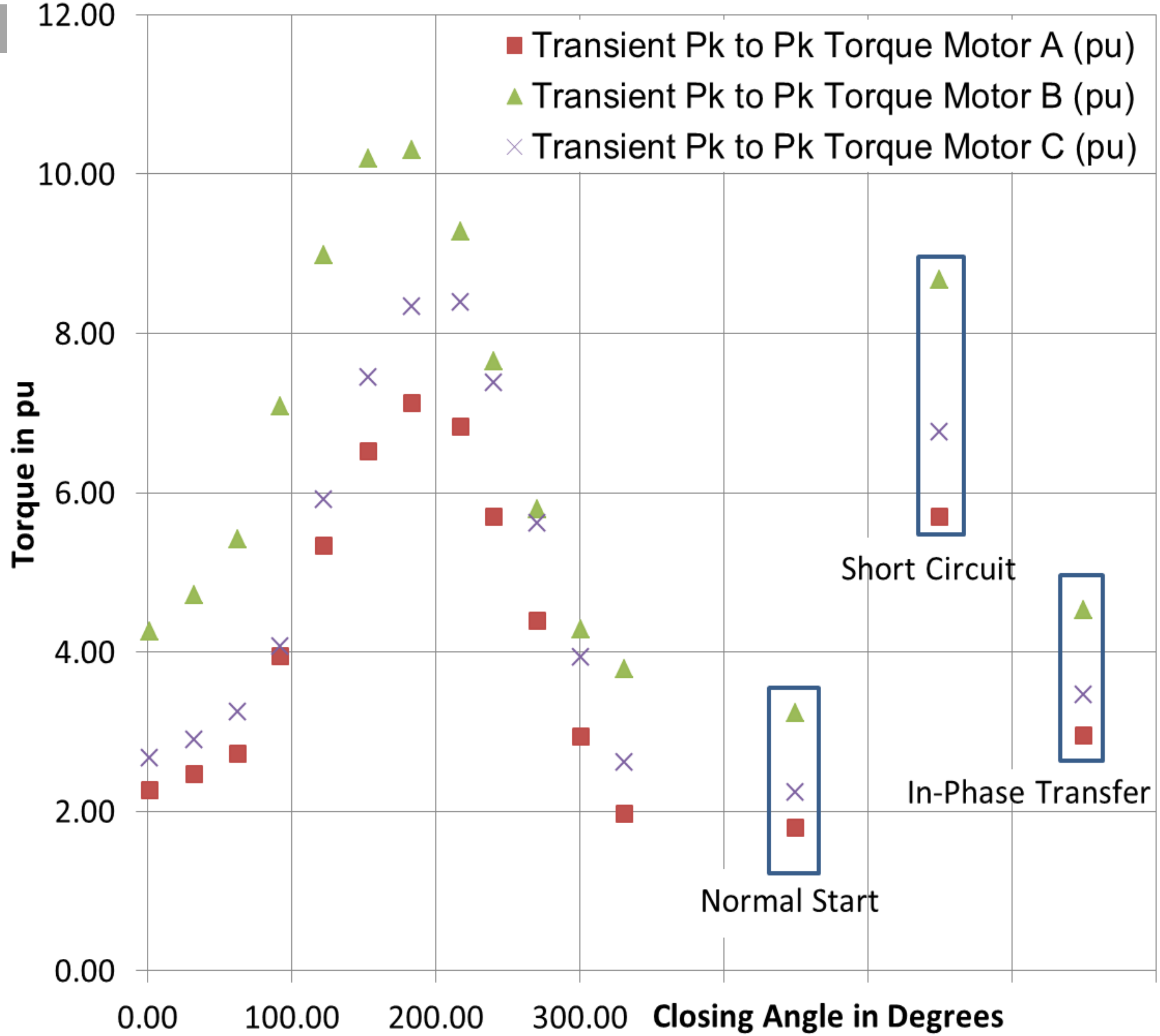
- **The peak-to-peak torque developed during the Residual Voltage Transfer is higher than the Three-Phase Short Circuit Torques in 40% of cases.**
- **As the nature of these torques are cyclic or pulsating, it could generate high mechanical vibration resulting in possible cumulative damage to the motors and any mechanical equipment connected to it.**
- **The peak current in motors during Residual Voltage Transfers is higher than the Three-Phase Short Circuit Currents in more than 60% 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.**

Test Results: <u>Transient Currents</u> During Residual Voltage Transfer Compared



Motor Modeling

Test Results: <u>Transient Torques</u> During Residual Voltage Transfer Compared



Motor Modeling Test Results Confirm the Motor Torque Ratio T_{PK} / T_L Conclusions

- **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.**
- **In-Phase Transfers always occur at much lower torques than the "blind" Residual Voltage Transfer method, closing at larger angles.**

Motor Bus Transfer Results Related to ANSI/NEMA Standard C50.41-2012

14.2 Slow Transfer or Reclosing

"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**… at the instant the transfer or reclosing is completed **does not exceed 1.33** per unit volts per hertz…**"**

TEST Results

- **Very high inrush currents and torques can occur at V/Hz levels ranging from 0.9 pu to 1.33 pu for the worst torques at a 183° close.**
- **The C50.41 pu V/Hz limit of 1.33 pu is of NO use as a measure to determine if the transient torques and currents exceed the design limits.**

Motor Bus Transfer Results Related to ANSI/NEMA Standard C50.41-2012

14.2 Slow Transfer or Reclosing

"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… **accomplished by a time delay relay equal to or greater than 1.5 times the open-circuit alternating-current time constant of the motor."** ***[22.3% of rated bus voltage or 26.8 Vac on 120 Vac PT]***

TEST Results

- **Significantly out-of-phase Residual Voltage Transfers, even with transfer breaker closing below 30% voltage, the motors still experience damaging multiples of rated current and torque.**
  - **Higher than Three-Phase Short Circuit Torque in 40% of cases**
  - **Higher than Three-Phase Short Circuit Currents in >60% of cases**
  - **Six times rated current in 89% of the cases**

Motor Bus Transfer Results Related to ANSI/NEMA Standard C50.41-2012

14.3 Fast Transfer or Reclosing
“occurs within a time period of 10 cycles or less.”

TEST Results

- **The In-Phase Transfer took more than 27 cycles.**
- **The bus voltage at the point of In-Phase Transfer is 62% compared to <30% for a Residual Voltage Transfer.**
- **For all motors, the peak currents for In-Phase Transfers are all lower than the Normal Start currents, and all much lower than currents for Residual Voltage Transfers.**
- **For the three motors, the peak-to-peak torques for In-Phase Transfers are only 2.95, 3.46, and 4.53 times rated torques.**
- **This 10-cycle time period would reject perfectly good In-Phase Transfers.**

Motor Bus Transfer Results Related to ANSI/NEMA Standard C50.41-2012

14.3 Fast Transfer or Reclosing

“occurs within a time period of 10 cycles or less.”

DISCUSSION

This 10-cycle time period assumes the initial phase angle between the motor bus and the new source starts somewhere near zero, and thus completes the transfer before the angle has a chance to increase to a damaging level.

But even at a medium inertia frequency decay of 20 Hz/sec, the angle movement in 10 cycles is a dangerous 100°, so 10 cycles is not a safe limit for fast transfer.

But as IEEE C37.96 reveals, due to the phenomena identified, the initial phase angle between the motor bus and the new source may be nowhere near zero, so 10 cycles or any time period never guarantees a good transfer.

Motor Bus Transfer Results
Related to ANSI/NEMA Standard C50.41-2012

14.3 Fast Transfer or Reclosing
"occurs within a time period of 10 cycles or less."

DISCUSSION (continued)

Fortunately, given these phenomena, an Open Transition Transfer allows the motors to spin free and rotate back through synchronism where the backup source breaker can always successfully be closed by the synchronous In-Phase Transfer method.

Motor Bus Transfer Results Related to ANSI/NEMA Standard C50.41-2012

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”
- “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…”

TEST Results

- Yes, even at voltages <30%

Residual Voltage Transfer Test Conclusions

High Currents:

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

High Torques:

- More than 40% probability of producing motor torques greater than short circuit torque
- 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 up 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.

Motor Bus Transfer Tutorial

Thomas R. Beckwith
Beckwith Electric Company
Author

Mohamed Abdel Khalek Mohamed
Beckwith Electric Company
Presenter

Questions?