KBR

Distribution System Development & Preliminary Studies

IEEE CED
January 27, 2016
(second night)

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Agenda

- Distribution System Development
- Modeling Data
- Studies Overview
- Typical Studies (LF, MS, SC)
- Optional (Coordination, AF, Harm, Stability)

Distribution System Development

Distribution System Development

Where is the power coming from?

- Existing utility connection
    - What is the voltage level, available capacity?
- New utility connection
    - Is there a nearby utility line or substation? Is the voltage level appropriate for the total load of the new system? Has the utility been contacted?
- Islanded generation
    - Is there black start power available? Will there be N+1 generators installed?
- Generation operated in parallel with the utility
    - Is the local generator just for backup? If it runs continuously, does the utility need to back it up in the event of a trip? Has all of this been discussed with the utility?

Distribution System Development

Where is the utility substation located?

- Utility substations are typically fed by open-air high-voltage lines.
- Routing open-air lines through an industrial facility is impractical
- Utility substations are therefore almost always located near the perimeter of the plot.

Distribution System Development

How many distribution & utilization substations are needed?

- What is the total load of the plant?
  - This drives the voltage level of the main distribution sub.
- What is the total load at each voltage level?
  - This drives the number of utilization subs at each level.
- How large is the plot?
  - This primarily affects LV subs via voltage drop on the branch circuits.
- How tight is the plot?
  - The Piping folks may push to use fewer and larger subs.
- Where are the loads located?
  - Affects organization of loads on load centers.

Distribution System Development

What type of distribution system is desired?

- Double-ended, radial, loop-fed?
  - Double-ended systems are most commonly used where high reliability/availability are desired.
  - Radial systems are used when lower cost is desired and availability/maintenance are less critical.
  - Loop-fed systems are used when cost is critical and availability/maintenance are secondary.
- For double-ended systems, are the tie breakers normally-open or normally-closed?
  - SC currents are higher when the tie breaker is closed.
  - IEEE 666 allows for the temporary paralleling of the two sources during maintenance transfers to be ignored, but some clients still want fully rated gear.
  - Protection schemes are different for systems with normally-closed ties.

Continuous & SC rating limits

- LV switchgear breaker ratings are defined in IEEE C37.16
  - Continuous ratings available up to 6000 A (w/fan cooling)
  - Short-circuit ratings up to 200 kA for fused breakers
  - A typical maximum of 4000 A and 65-100 kAIC is more common.
  - A 4000 A bus is common for 2500 kVA transformers with fan cooling.
  - Due to arc-flash the trend is to smaller LV transformers
- LV MCC ratings are per NEMA ICS 1 and ICS 2.
  - The typical highest continuous bus rating is 3000 A.
  - The highest SC rating is 200 kA though 65-100 kA are more common.

Distribution System Development

Continuous & SC rating limits

- MV switchgear breaker ratings are per IEEE C37.04 & 06
  - Continuous ratings available up to 4000 A (w/fan cooling)
  - Short-circuit ratings up to 63 kA at 5-15 kV, 25 kA at 27 kV, & 40 kA above
  - A typical maximum of 3000 A and 50 kAIC is more common for 5 & 15 kV.
- MV MCC ratings are per ICS 1 and ICS 3.
  - The typical highest continuous bus rating is 3000 A
  - SC ratings are typically 40 or 50 kAIC

Distribution System Development

Selecting an appropriate primary distribution bus voltage

- The maximum load that can be fed by a given load center depends on its continuous current rating and its voltage level.
- Assume a total plant load of 10 MVA…
  - At 480 V this would require a bus rating of 12,048 A.
  - At 4.16 V this would require a bus rating of 1388 A.
  - At 13.8 kV this would require a bus rating of 418 A
  - Unless dictated by other factors, a 4.16 kV main bus at 2000 A looks most appropriate.
- Other factors could include large motor starting or SC limitations.
  - If the 10 MVA load is comprised of a single, MV motor rated at 8000 hp with the rest of the loads at 480 V then a 13.8 kV main bus would be appropriate.

Distribution System Development

Selecting an appropriate primary distribution bus voltage

- Consider a system with 60 MVA of total operating load…
  - The bus rating required for at 13.8 kV is 2510 A. Selection of a 3000 A bus would be appropriate.
  - If the system is fed by two 30 MVA transformers with a normally-open tie breaker then the max SC current (including one transformer and all motors) could be on the order of 45 kA.
  - If the system uses a normally-closed tie, the SC current could be on the order of 50 kA.
  - MV gear up to 63 kA is available, but is not necessarily from all suppliers.
  - If the system is supplied by local turbine generators, then the high X/R ratio and requirement for N+1 generators on-line could result in 63 kA gear not being suitable.
  - Ultimately it might be necessary to consider 34.5 kV gear due SC limitations.

Sizing buses to match transformer ratings

- Bus ratings should usually be selected align with the transformer maximum rating.
  - A 1500 kVA, ONAN transformer has a full load current (FLC) of 1804 A at 480 V. Select 2000 A bus.
  - A 1500 kVA ONAN/ONAF, 55/65 ˚C transformer has an FLC of 2324 A at 480 V. Select 2400 A or 3000 A bus.
  - A 12.5 MVA, ONAN transformer has an FLC of 1735 A at 4.16 kV. Select a 2000 A bus.
  - A 12.5 MVA, ONAN/ONAF, 55/65 ˚C transformer has an FLC of 2435 A at 4.16 kV. Select a 3000 A bus.

Modeling Data

Modeling Data

Utility data

- Max SC contribution (& X/R) for worst-case SC study
  - If necessary, use maximum equipment rating at the associated voltage level.
- Min SC contribution (& X/R) for worst-case motor starting study
  - No safe way to assume minimum SC value
- Normal & abnormal operating voltages
  - Don’t assume normal voltage is the nominal voltage; normal may be slightly above nominal; example – 141 kV on a 138 kV system (102%)
- Voltage drop limits for normal & contingency conditions
  - Example – 1.5% during normal two-line conditions, 2.0% during contingency single-line conditions

Modeling Data

Generator data

- Differentiate/confirm driver versus generator ratings
  - Turbine output is usually less than the generator nameplate rating.
- Generator X”d used for SC studies, X’d used for motor starting studies.
  - Standard manufacturing tolerance is +/-15% as defined in IEEE C50.13
  - Lower tolerances (typically 10%) may be defined on the generator datasheet
  - X/R needed to accurately calculate peak & adjusted interrupting duties.
  - In the absence of supplier quoted data, use previously quoted data.
  - If necessary based on study results, make sure the Machinery group defines reactance limits in RFQ packages
- Additional data including inertia and dynamic models for AVR and governor is required for transient studies.

Modeling Data

Transformer data

- Use standard sizes and cooling class ratings
  - IEEE sizes defined in IEEE C57.12.00-2010 (liquid immersed) & IEEE C57.12.01-2005 (dry type)
  - IEC sizes defined in IEC 60076-1:2011
  - Cooling classes per IEEE C57.12.00-2010 & IEC 60076-2:2011
  - IEEE units are rated on output power per IEEE C57.12.00-2010, Section 5.4.1 (liquid immersed) & IEEE C57.12.01-2005 (dry type), Section 5.4.2
  - IEC rated on input power per IEC 60076-1:2011, Section 5.1.1
- Select voltage ratings per applicable standard
  - IEEE secondary voltage matches bus voltage
  - IEC secondary voltage typically higher than bus voltage

Modeling Data

Transformer data

- Use standard impedances
  - IEEE impedances defined in IEEE C57.10 (power) & C57.36 (distribution)
  - IEC based on IEC 60076-5:2006
  - Include a manufacturing tolerance of +/-7.5% for IEEE units per IEEE C57.12.00-2010 (liquid immersed), Section 9.2 & IEEE C57.12.01-2005 (dry type), Section 9.2
  - For IEC units include a tolerance of +/-10% for impedances less than 10% and +/-7.5% for impedances 10% and above.
- LTCs are typically located….
  - In the secondary winding for IEEE transformers per C57.12.10-2010 (liquid immersed), Section 4.5.2
  - In the primary winding for IEC transformers
  - Note that when located in the primary winding there is a significant impact on the transformer impedance depending on tap position.

Modeling Data

Transformer data

- Generator unit transformers (UTs or GSUs) typically….
  - include two banks of fan cooling,
  - use de-energized tap changers (DETCs), but may include load tap changers (LTCs),
  - and have impedances specifically selected to optimize reactive power transfer (refer to IEEE C57.116-2014)
- Captive transformers…
  - can be used to shift voltage drop during motor starting from the distribution bus to the motor terminals
  - IEEE paper "Design and Protection of Captive Motor – Transformers". IEEE Transactions on Industry Applications, Vol. 36, No. 6, November/December 2000.

Modeling Data

Motor voltage selection

- Design guides typically recommend the following motor size and voltage breakpoints for domestic systems.
  - 460 V – ½ hp through 200 hp or 250 hp
  - 4000 V – 250 hp through 5000 hp
  - 13.2 kV – above 5000 hp
- The design of the actual distribution system can affect these breakpoints.
  - Smaller source transformers will reduce starting capacity and thus the maximum motor size that can be started.

Modeling Data

Medium-voltage motors/loads

- Can usually individually model MV loads
  - There are relatively few MV motors and loads compared to LV.
  - Allows use of individual locked-rotor currents, typically 650% worst-case.
  - Specific LRCs can be defined for selected loads as needed for motor starting studies.
  - If loads are very poorly defined, lumped loads can be used similar to LV modeling.
- Typically assume a minimum motor terminal voltage during starting of 80% (on motor base).
  - Should confirm this is how the motors are specified and quoted.
  - Motors on captive transformers/systems can be specified with even lower minimum voltages, such as 70%.
  - Client requirements may dictate that a higher voltage must be maintained during starting, such as 85%.

Modeling Data

Low-voltage motors/loads

- Can usually model as lumped loads
    - Separate out largest motor if necessary for motor starting cases.
    - Some clients may require that all motors 50 hp and larger be individually modeled.
    - Motor-driven loads are constant-kVA – their FLC will increase/decrease with lower/higher voltage applied.
    - Static (non-motor) loads are constant impedance – their power varies with voltage.
- Motor and static loads can be separately modeled or in a single lump with assigned split factor.
    - Assuming 100% motor load is conservative for SC studies.
- Locked-rotor currents
    - Use typical 650% for individually-modeled motors
    - Can use 25% for lumped loads per C37.13 xxxxxx

Modeling Data

Cables

- Typically only major distribution system cables of significant length need to be included.
  - Short runs of transformer primary and secondary cables are insignificant compared to the impedance of the transformer, especially considering the manufacturing tolerance.
  - Motor branch circuits only need to be included for motors considered in the motor starting study.
- Supplier-specific impedances are not necessary
  - When cable impedances are marginally significant, the difference in impedances for a given size are even less significant.

Modeling Data

Other factors

- How much conservatism to include?
  - Using multiple worst-case conditions and assumptions may not be realistic.
  - As an example, having the simultaneous occurrence of the minimum utility SC contribution, minimum utility operating voltage, and multiple double-ended substations operating single-ended may be too much.
  - Whatever is decided, the study cases should be explicitly defined in the written report.
- Performing the various studies can take an iterative approach
  - All performance criteria must be simultaneously met.
  - Solving an issue with one study could negatively impact others.
  - Every time a rating is adjusted, all associated cases should be repeated.

Studies Overview

Typical Preliminary Studies

What studies are essential in the development of the distribution system design?

- Load Flow
  - Determines if equipment continuous operating ratings (continuous bus ratings, transformer sizes, etc.) are adequately selected and that acceptable voltage regulation can be maintained at all levels of the system.
- Motor Starting
  - Determines the maximum voltage drop on the system during starting of the largest motors.
- Short-Circuit
  - Determines if equipment fault duty ratings (momentary device duties, interrupting device duties, bus withstand, etc.) are adequately selected for the worst-case short-circuit levels.

Optional Studies

What other studies might be requested during FEED?

- Overcurrent Device Coordination
  - Not typically performed during FEED, but may be required to facilitate arc-flash studies.
- Arc-Flash
  - Might need to be evaluated during FEED if incident energy levels are required to be kept under certain limits (e.g. 8 cal/cm^2). These studies can also aid in selection of active vs. passive protection and evaluate if maintenance mode OC settings are required.
- Harmonic
  - Not typically performed during FEED unless there is a significant VFD load on the system and the utility has strict requirements on the levels of harmonic distortion.
  - Of more value when a preferred drive topology and/or supplier is pre-determined.
  - Of more value with when there are significant cap banks on the system.

Optional Studies

What other studies might be requested during FEED?

- Transient Stability
  - Unless the generator supplier has been determined, all generator and dynamic control data must be assumed.
  - For industrial systems most cases evaluate the system frequency and voltage responses to step-load additions and rejections.
  - Angular stability is considered primarily only via critical clearing time cases.

Load Flow Studies

Load Flow Studies – Study Cases

What operating cases need to be considered for load flow studies?

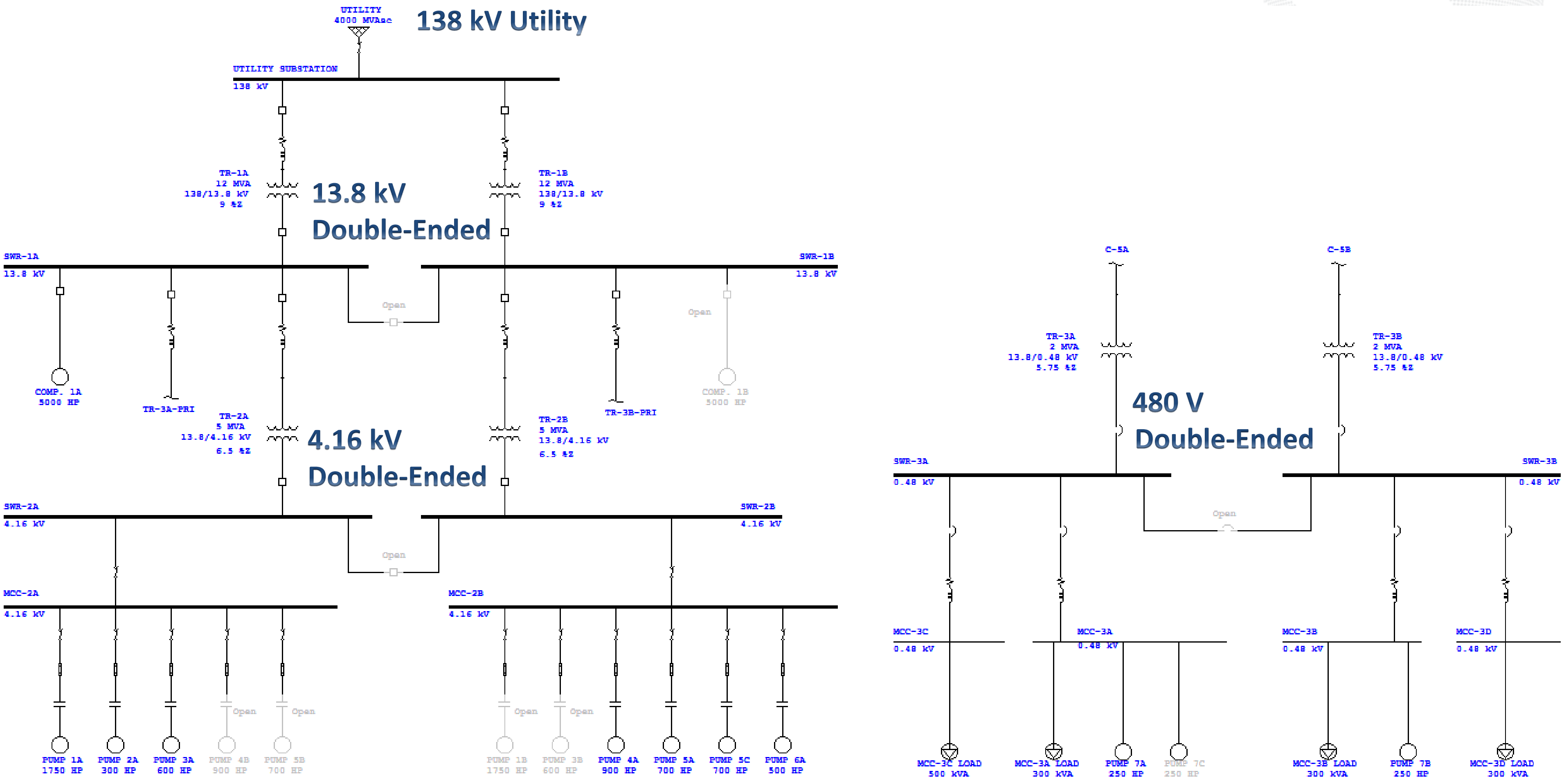
- Normal Operation
  - All normally-operating sources and distribution equipment are in service.
  - Double-ended substations are operated with both transformers in service and the bus tie breaker open.
  - Transformer tap changers are set to maintain nominal secondary voltage levels for normal operating load.
  - Case identifies normal loading on equipment.
- Contingency Operation
  - One or more sources and selected distribution equipment are out of service.
  - Double-ended systems are operated single-ended with one source out of service and the bus tie breaker closed.
  - Case provides worst-case equipment loading and worst-case (though possibly overly conservative) system voltages.

Load Flow Studies – Study Cases

What operating cases need to be considered for load flow studies?

- Essential / Backup Operation
  - Utility sources not in service
  - Backup generators in service to supply essential and/or emergency loads only
- Utility Sources
  - Max & Min utility source impedances are not applicable for load flow cases; the source bus voltage is held constant by the swing source.
- Impedance Tolerances
  - Can be used but are not as critical as for motor starting and short-circuit cases.

Load Flow Studies – Example System



138 kV Utility

13.8 kV Double-Ended

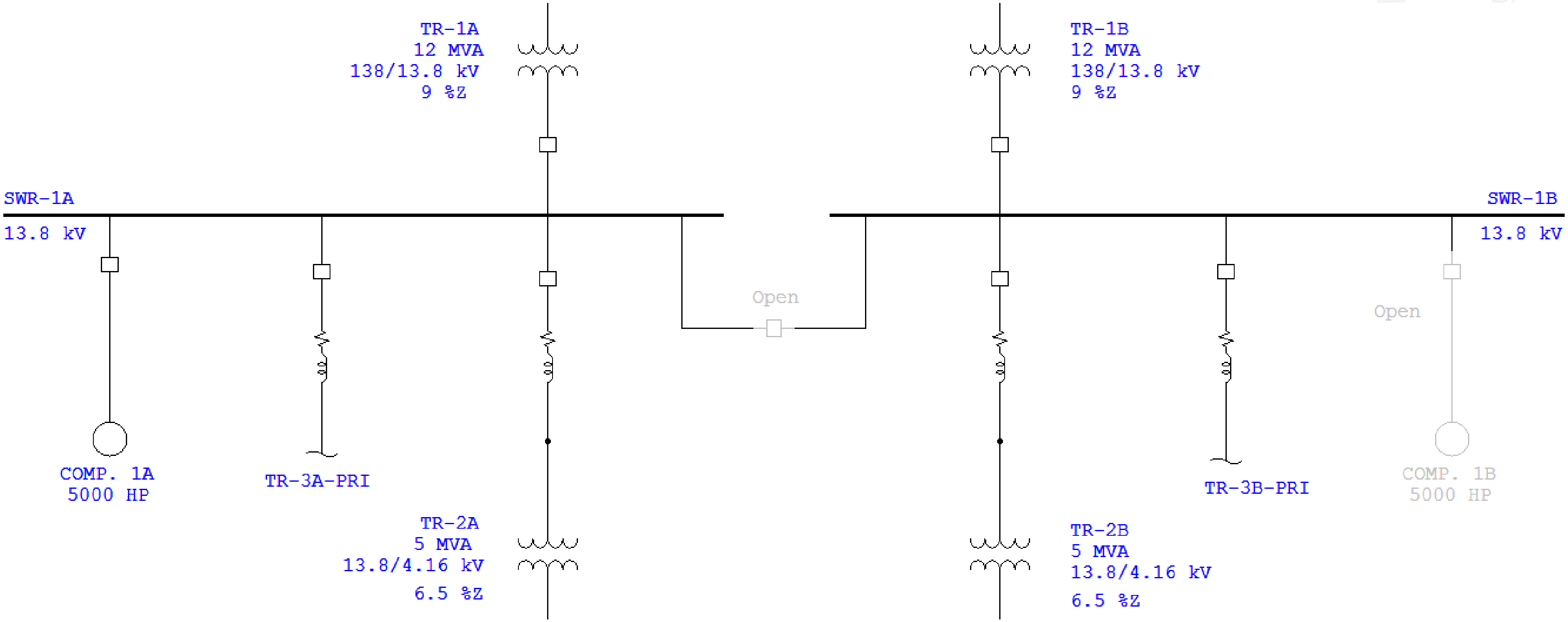
4.16 kV Double-Ended

480 V Double-Ended

Load Flow Studies – Example System

Engineering & Construction

13.8 kV Double-Ended



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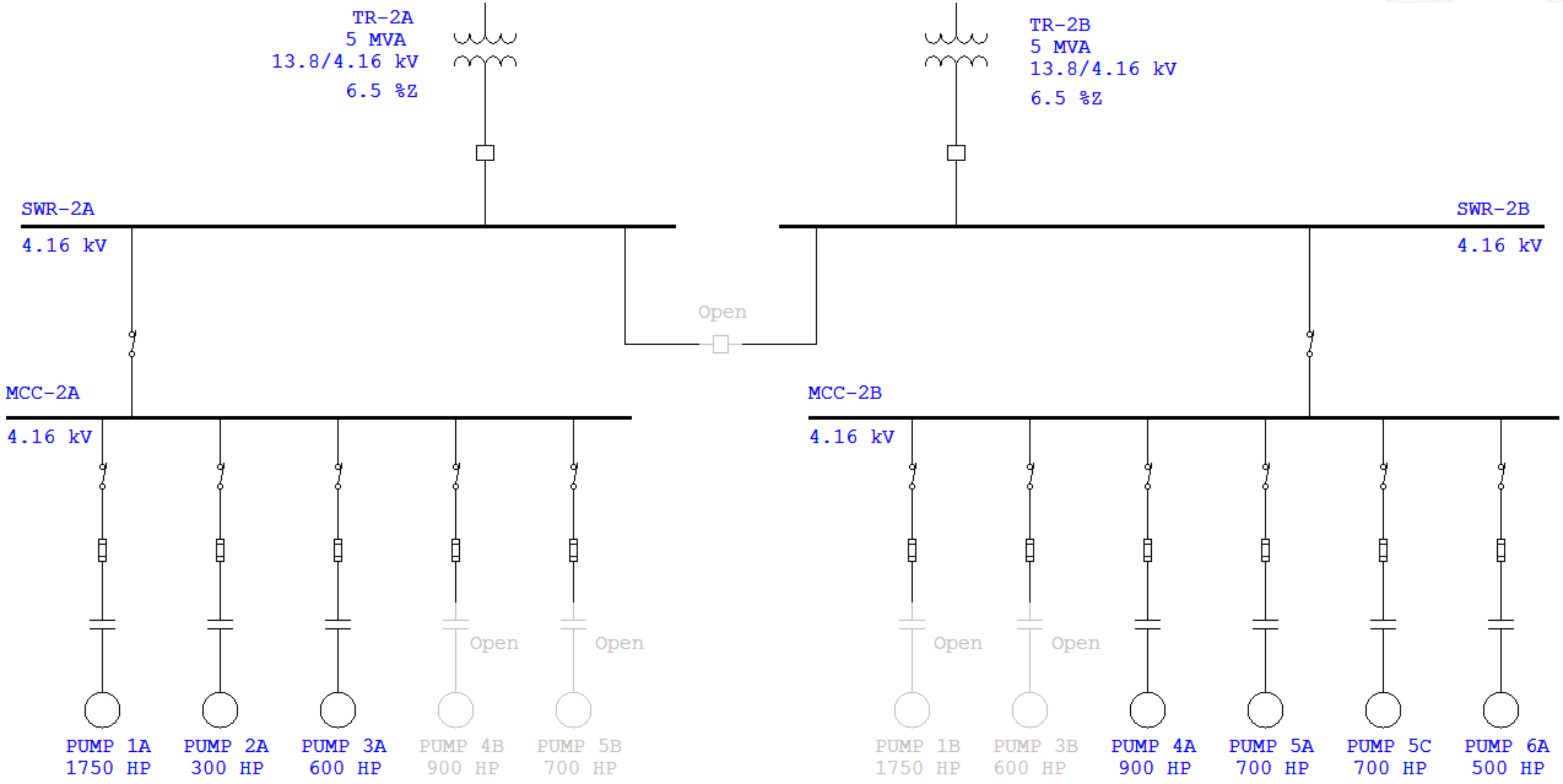
Load Flow Studies – Example System

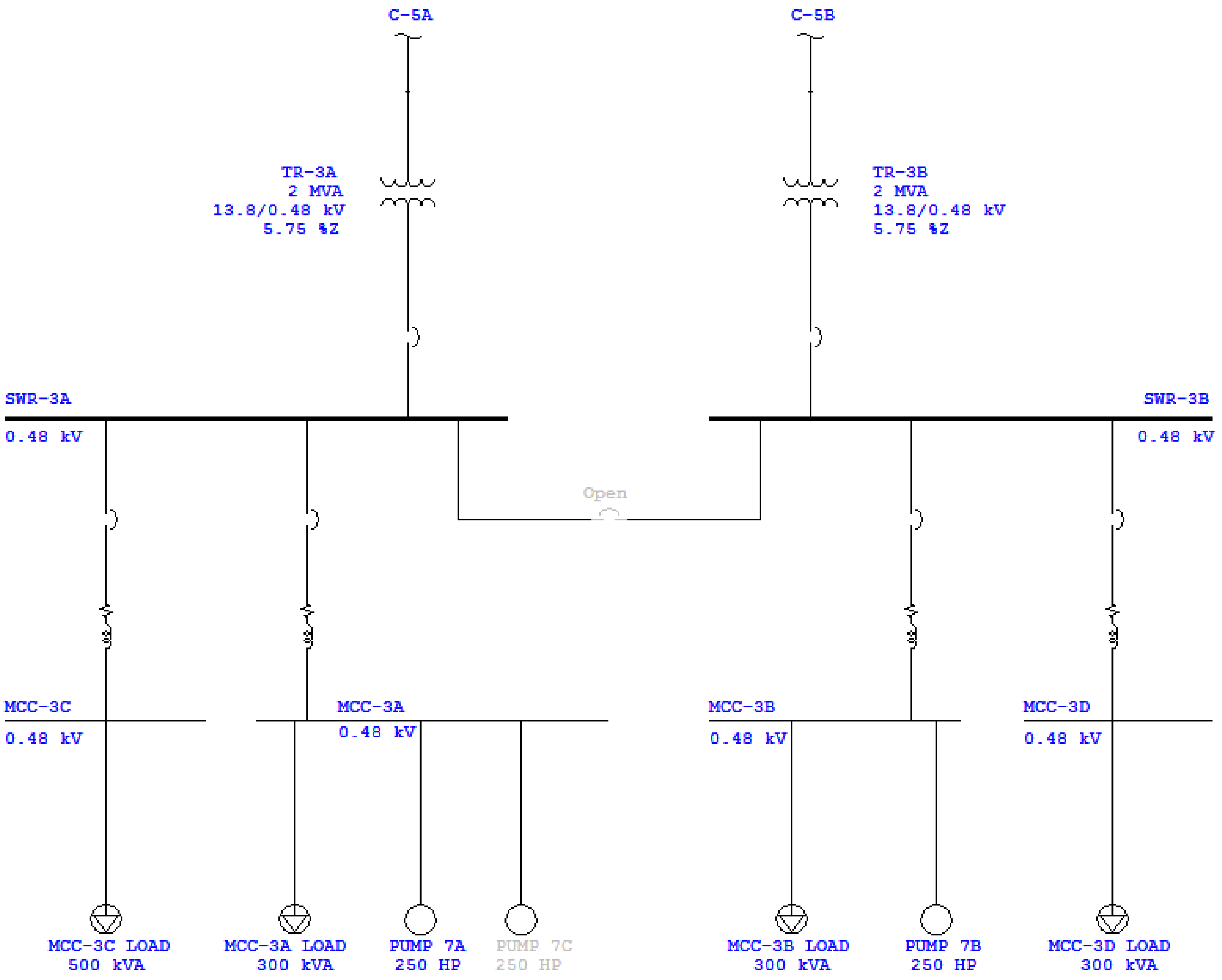
4.16 kV Double-Ended



Load Flow Studies – Example System

Engineering & Construction

480 V Double-Ended



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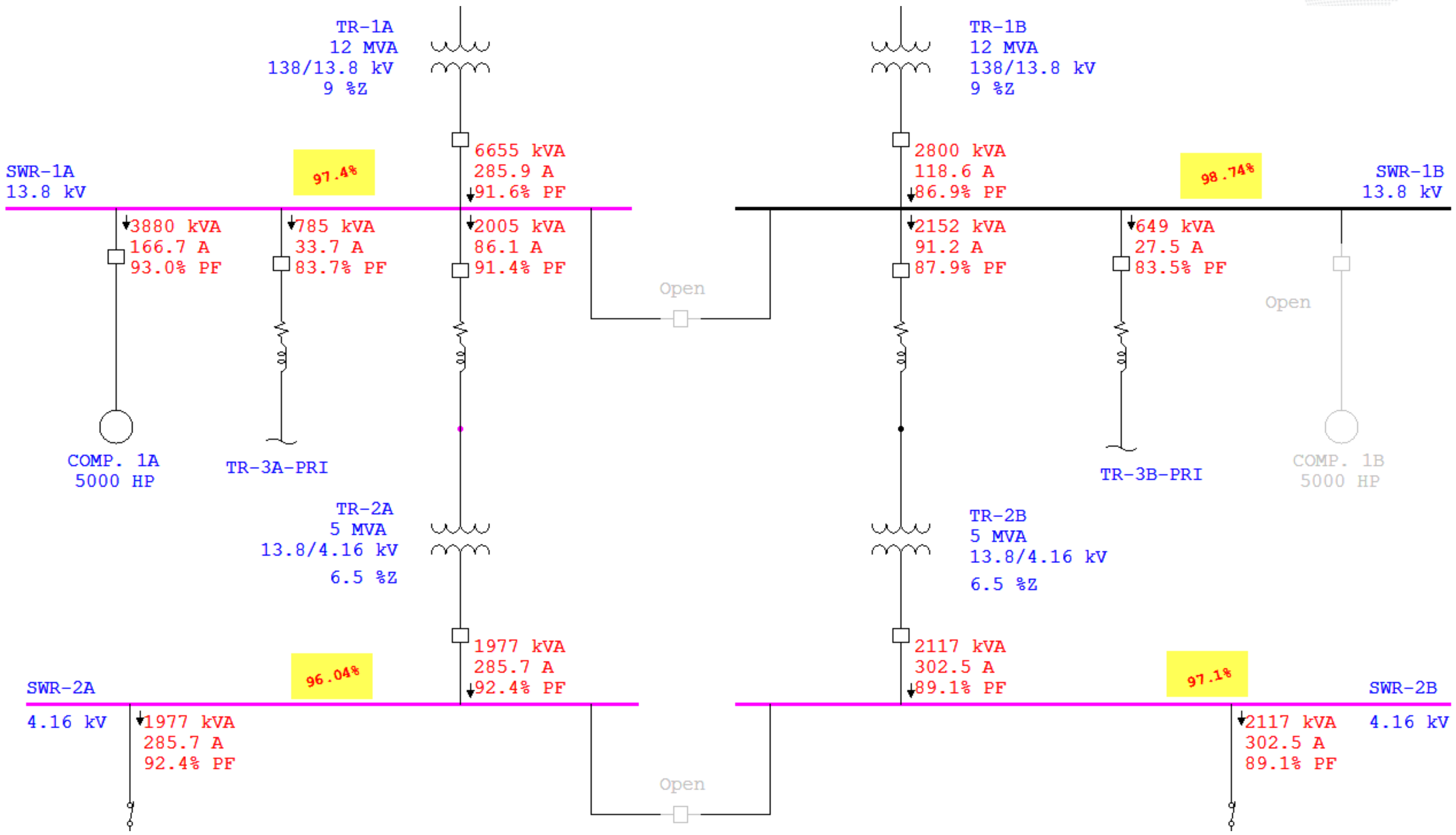
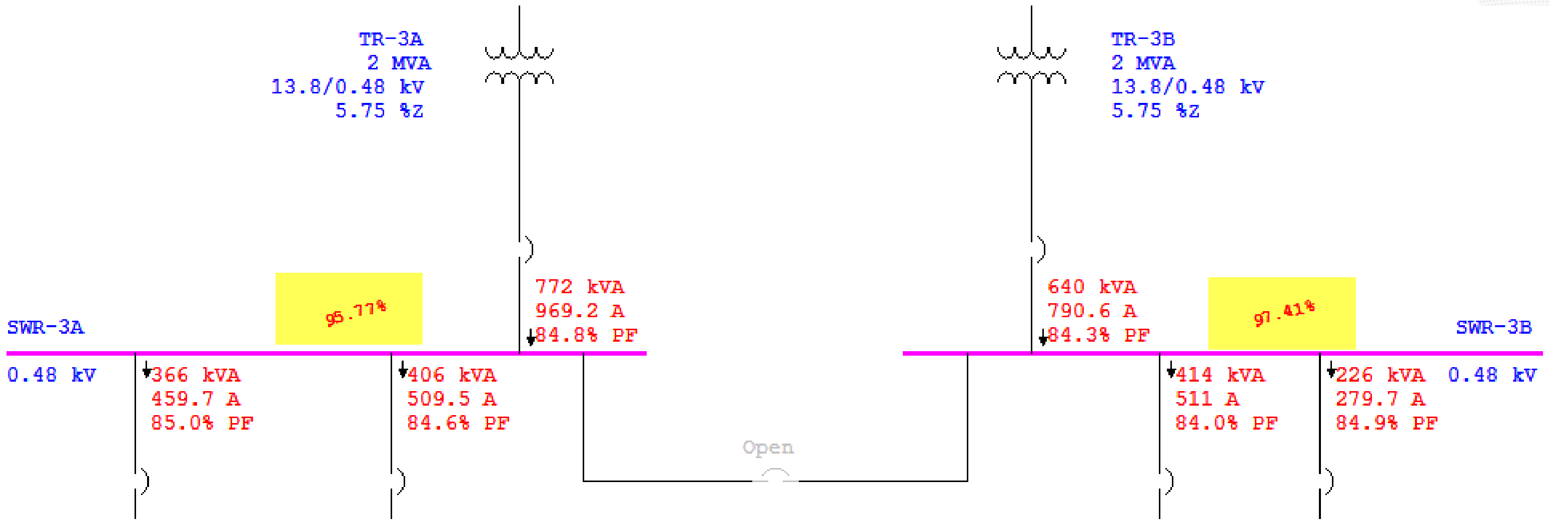
Load Flow Studies – Setting Transformer Taps

Normal operation with all transformer taps at nominal (0%)



Load Flow Studies – Setting Transformer Taps

Normal operation with all transformer taps at nominal (0%)

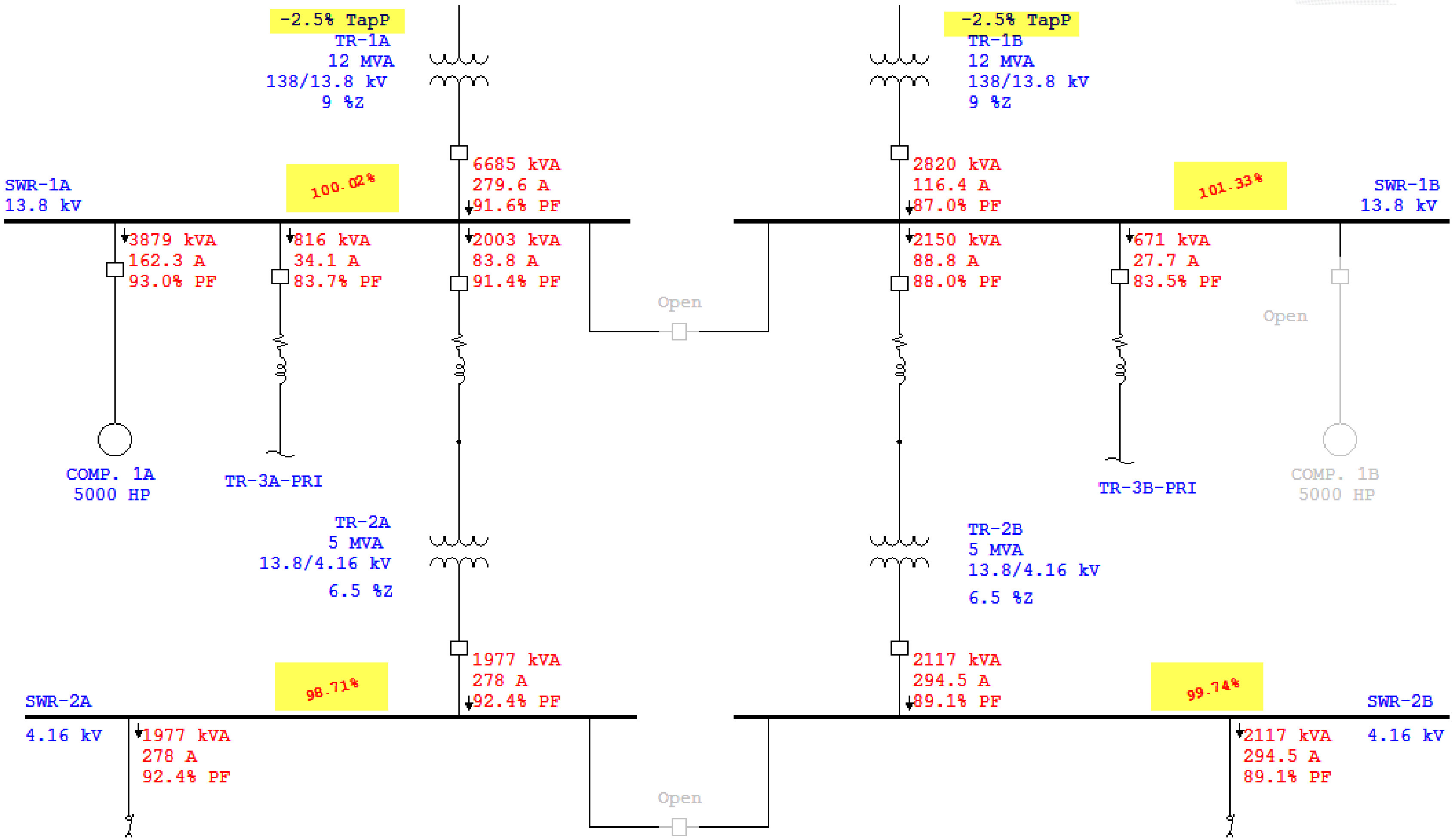


- All voltages are within the common +/-5% desired operating range, but all are below nominal.

Voltage Level	Lowest/Highest Bus Voltages (as % of nominal)
13.8 kV	97.40% / 98.74%
4.16 kV	96.04% / 97.10%
480 V	95.77% / 97.41%

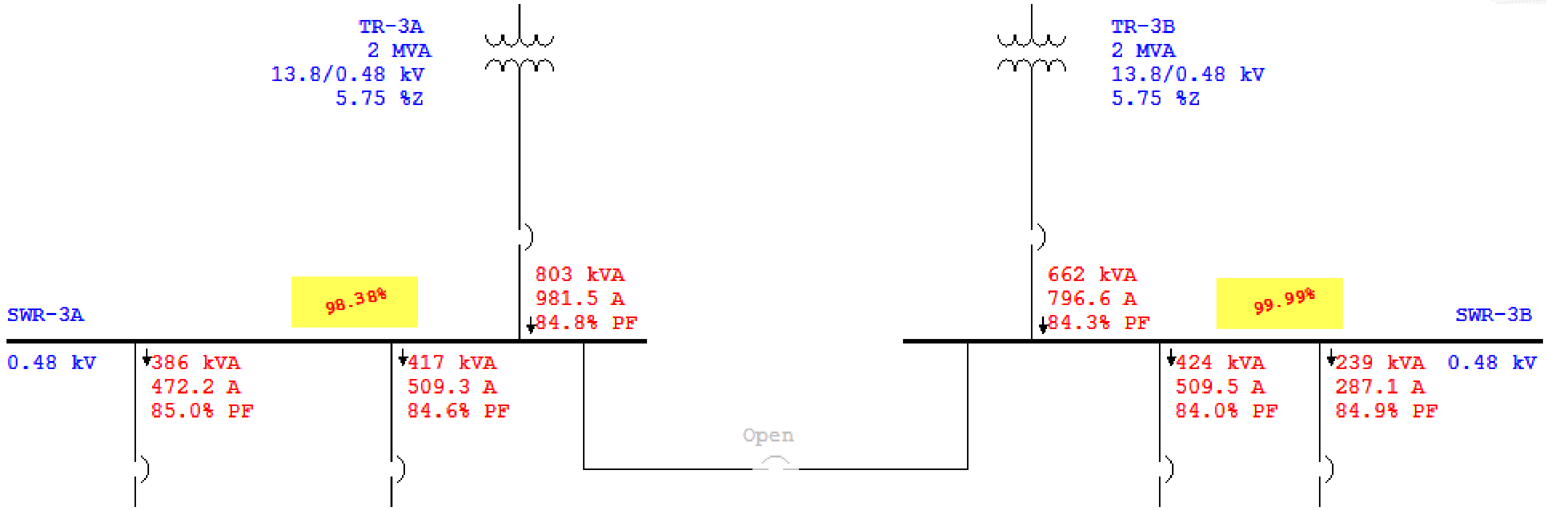
Load Flow Studies – Setting Transformer Taps

Normal operation with main transformer taps at -2.5%



Load Flow Studies – Setting Transformer Taps

Normal operation with main transformer taps at -2.5%

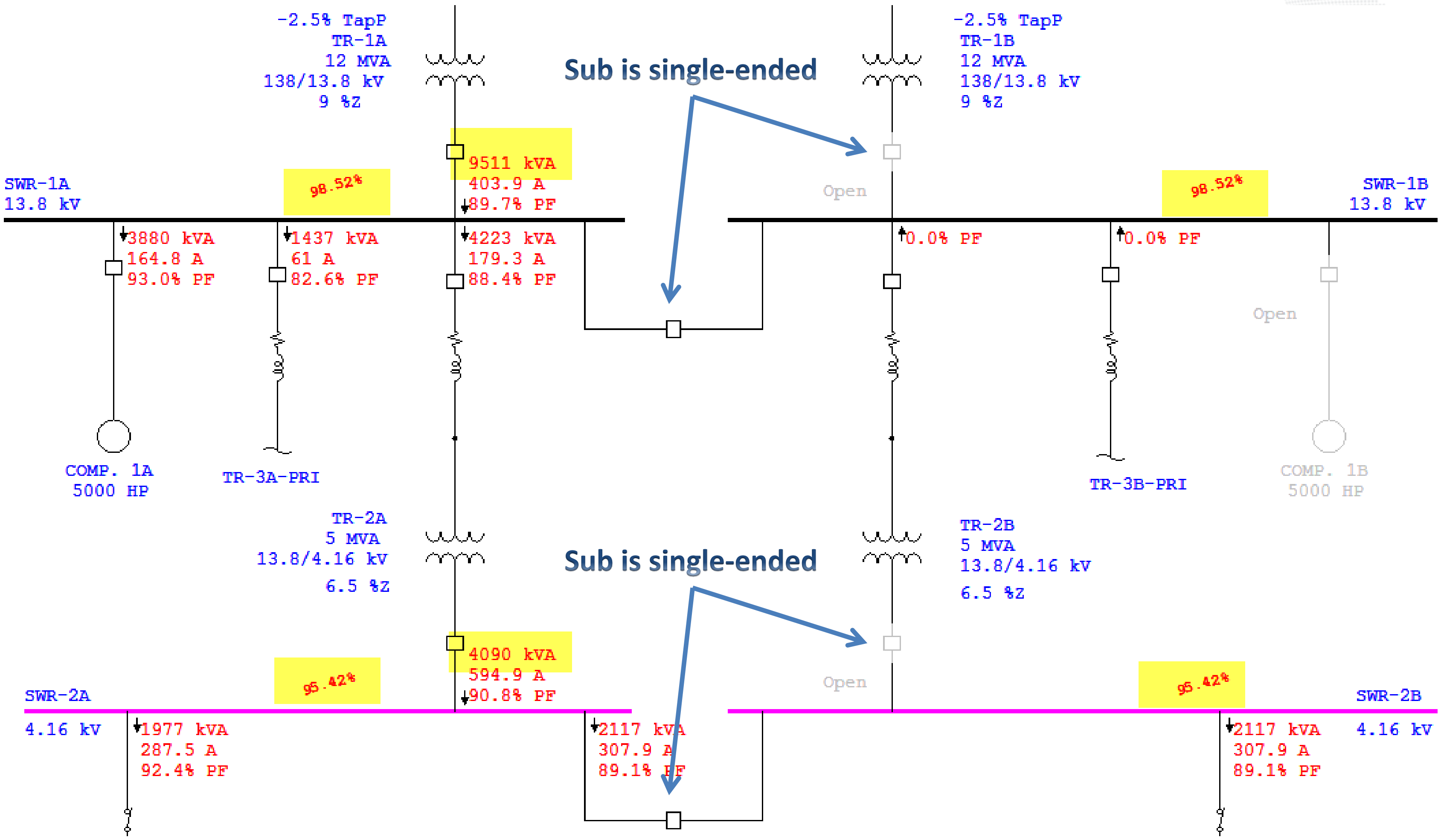


- All voltages are within the common +/-5% desired operating range, but all are below nominal.

Voltage Level	Lowest/Highest Bus Voltages (as % of nominal)
13.8 kV	100.02% / 101.33%
4.16 kV	98.71% / 99.74%
480 V	98.38% / 99.99%

Load Flow Studies – Single-Ended Operation

Single-ended operation with main transformer taps at -2.5%

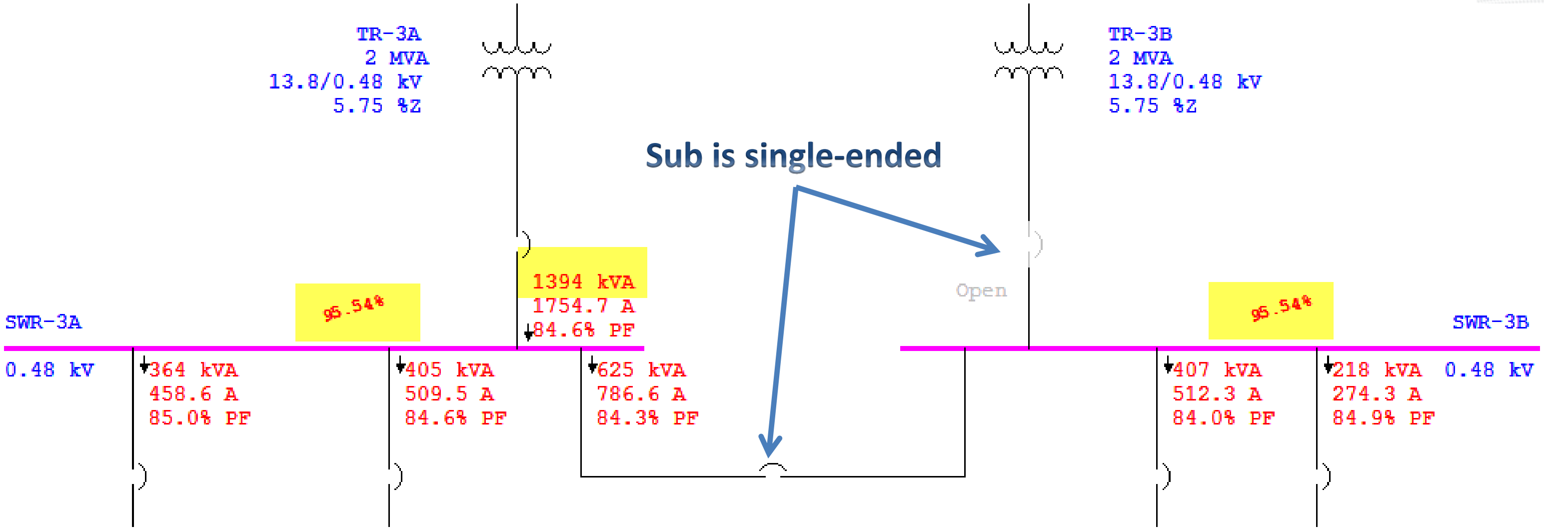


Sub is single-ended

Sub is single-ended

Load Flow Studies – Setting Transformer Taps

Single-ended operation with main transformer taps at -2.5%



- All voltages are within +/-5% of nominal...
- although having all substations single-ended at the same time is unlikely thus conservative.

Voltage Level	Lowest/Highest Bus Voltages (as % of nominal)
13.8 kV	98.52%
4.16 kV	95.42%
480 V	95.54%

Load Flow Studies – Transformer Loading

Based on the single-ended case loading

- All recommended transformer sizes are adequate for the preliminary load levels.
- There is approximately 20% margin for design allowance (see table below).
- If there is a requirement for spare capacity fan-cooling could be added.

Transformer	ONAN Rating	Max (Single-Ended) Operation
		Load (% of ONAN Rating)
138/13.8 kV	**12 MVA**	9.5 MVA (79%)
13.8/4.16 kV	**5 MVA**	4.1. (82%)
13.8/0.48 kV	**2 MVA**	1.4 (70%)

Load Flow Studies – Take-Aways

Things to remember

- Adjust transformer taps to maintain near nominal voltage during normal operation.
- Perform contingency case to determine worst-case equipment loading.
- Allow design margin for load growth during detailed design.
  - 15-20% margin is typical during FEED
  - Lower margins can be applied for MV loads when these are better defined
- Include margin for future load if required by client.

Motor Starting Studies

Motor Starting Studies – Dynamic vs. Static

- Dynamic Motor Starting
  - Requires dynamic motor model, load torque model and inertia.
  - Simulates acceleration of the motor.
  - Determines if motor can be started, acceleration time, and impact on system voltages during motor starting.
  - Not typically performed during preliminary studies due to lack of dynamic data.

- Static Motor Starting
  - Only data required is locked rotor current and minimum acceptable motor terminal voltage.
  - Assume typical 650% LRC for induction motors and 500% LRC for synchronous motors. Reduced LRCs can be recommended if needed.
  - Determines system and motor terminal voltages at the instant of motor starting.
  - Assume typical minimum motor voltage of 80% for starting. Acceleration time is not determined nor needed.

Motor Starting Studies – Study Factors

What factors need to be considered for motor starting studies?

- Worst-case operation
  - To minimize the number of cases required, consider only worst-case conditions.
  - For utility-fed systems typically consider the minimum MVA_{sc} , representing the maximum utility source impedance.
  - Avoid using the published minimum utility voltage unless it is confirmed with actual historical metering data. Published data, such as 95-105% of nominal is often unrealistic.
  - For generator-fed systems use the minimum number of units that may be online. For system with three generators in an N+1 system, start with at most two units online (N+0).
  - Single-end only the source substation. It is unrealistic to assume all substations will be single-ended.
  - When applicable, start the largest standby motor with the primary motor still in service.
  - Where applicable, perform cases for motors on essential generators.

Motor Starting Studies – Study Factors

What factors need to be considered for motor starting studies?

- System impedances
  - All significant branch impedances in the path between the utility source and the starting motor should be included.
  - Transformer primary and secondary cables can be omitted if relatively short (<100’).
  - The motor branch circuit cable should always been included. LV circuits have the most significant effect.
- Manufacturing tolerances
  - Since tested impedances are not available for grass-root FEED studies the maximum positive manufacturing tolerances should be used.
  - Be sure you know what your study software does with entered tolerances.

Motor Starting Studies – Acceptance Criteria

IEEE 399 – 1997 (IEEE Brown Book) provides the following guidance

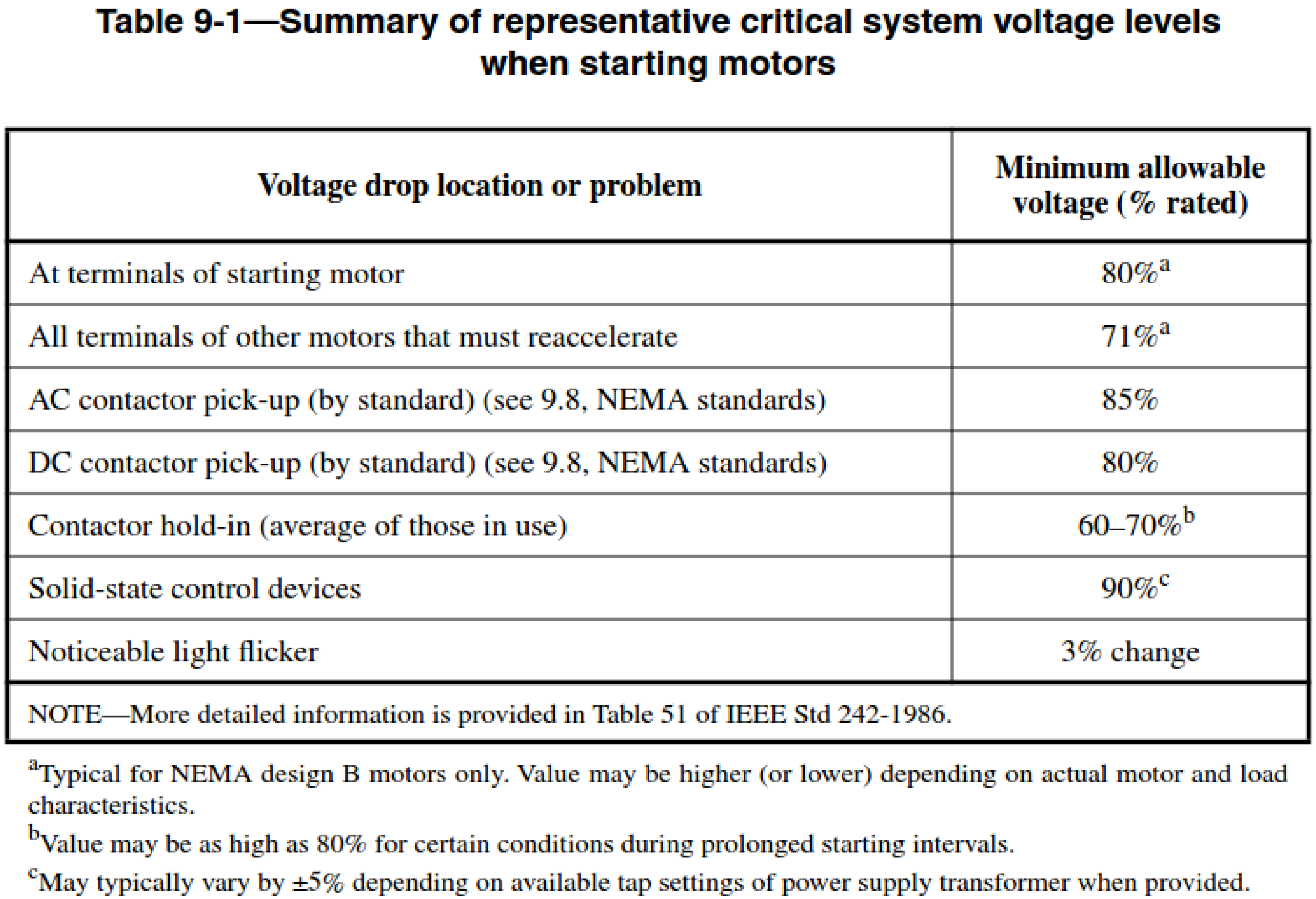


Table 9-1—Summary of representative critical system voltage levels when starting motors

Voltage drop location or problem	Minimum allowable voltage (% rated)
At terminals of starting motor	80%[a]
All terminals of other motors that must reaccelerate	71%[a]
AC contactor pick-up (by standard) (see 9.8, NEMA standards)	85%
DC contactor pick-up (by standard) (see 9.8, NEMA standards)	80%
Contactor hold-in (average of those in use)	60–70%[b]
Solid-state control devices	90%[c]
Noticeable light flicker	3% change
NOTE—More detailed information is provided in Table 51 of IEEE Std 242-1986.	

[a] Typical for NEMA design B motors only. Value may be higher (or lower) depending on actual motor and load characteristics.

[b] Value may be as high as 80% for certain conditions during prolonged starting intervals.

[c] May typically vary by ±5% depending on available tap settings of power supply transformer when provided.

Motor Starting Studies – Acceptance Criteria

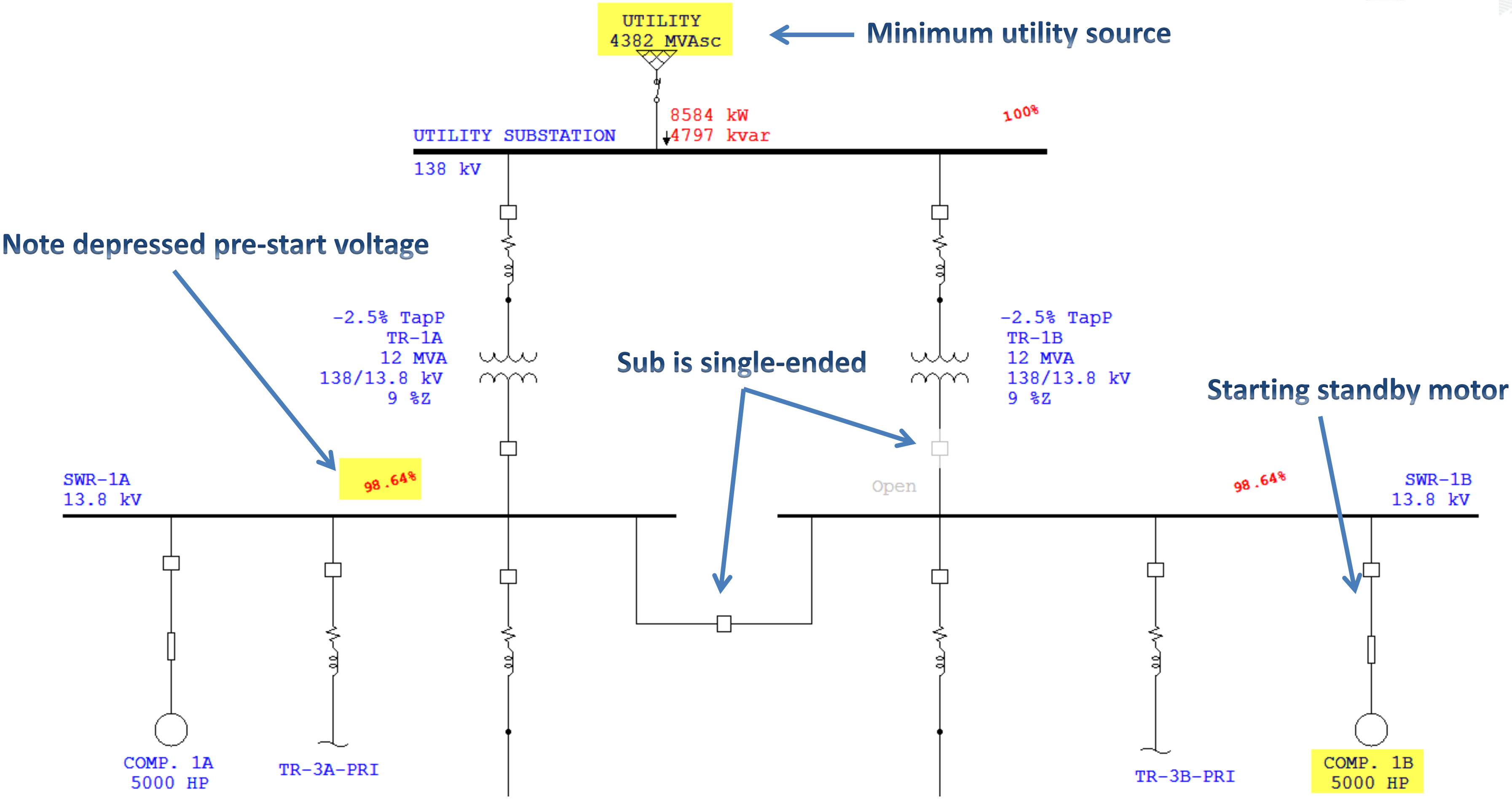
Clients often have more stringent criteria.

(though the basis for this not often defined)

Bus / Motor	Minimum Allowable Voltage During Motor Starting
34.5 kV Bus	90%
13.8 kV Bus	90%
4.16 kV Bus	85%
480 V Bus	85%
Motor Terminals (Motor Being Started)	85%

Motor Starting Studies – 13.2 kV Motor Example

Starting standby 5000 hp, 13.2 kV, 650% LRC motor under contingency operation (only 13.8 kV single-ended)



Minimum utility source

Note depressed pre-start voltage

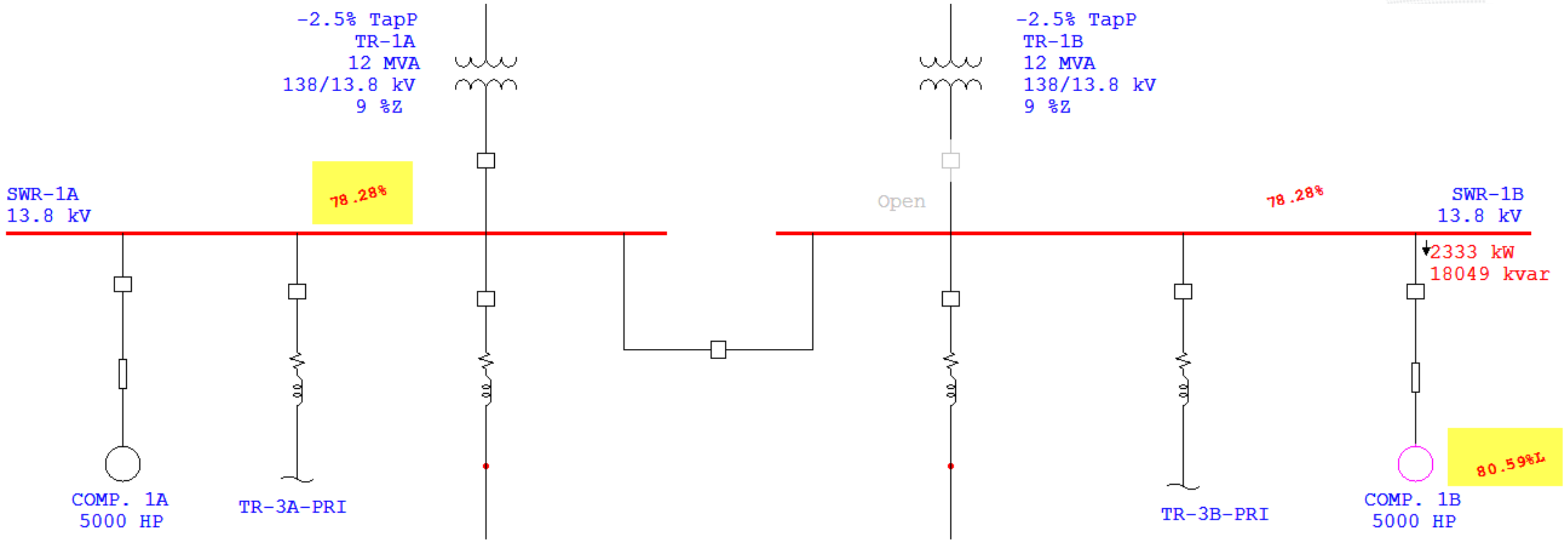
Sub is single-ended

Starting standby motor

Motor Starting Studies – 13.2 kV Motor Example

Engineering & Construction

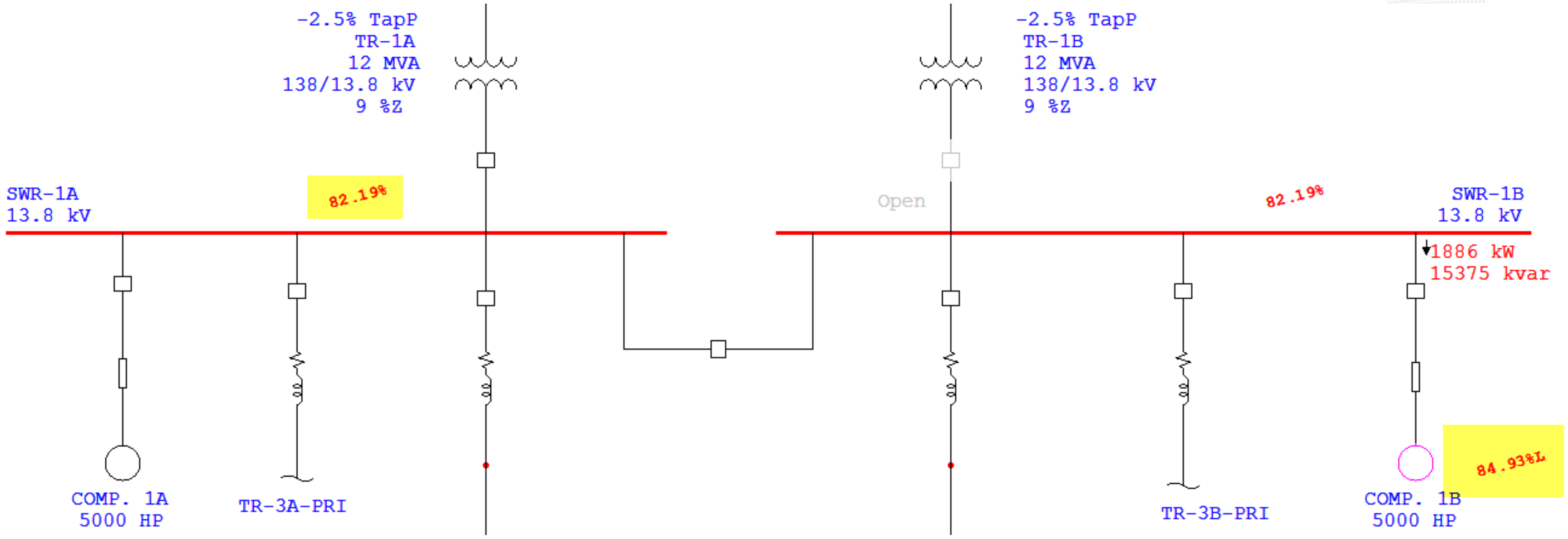
Starting standby 5000 hp, 13.2 kV, 650% LRC motor



- Motor voltage is above 80% and should be able to start.
- The system is acceptable per the Brown Book, but overall system voltage being below 80% is undesirable for FEED.

Motor Starting Studies – 13.2 kV Motor Example

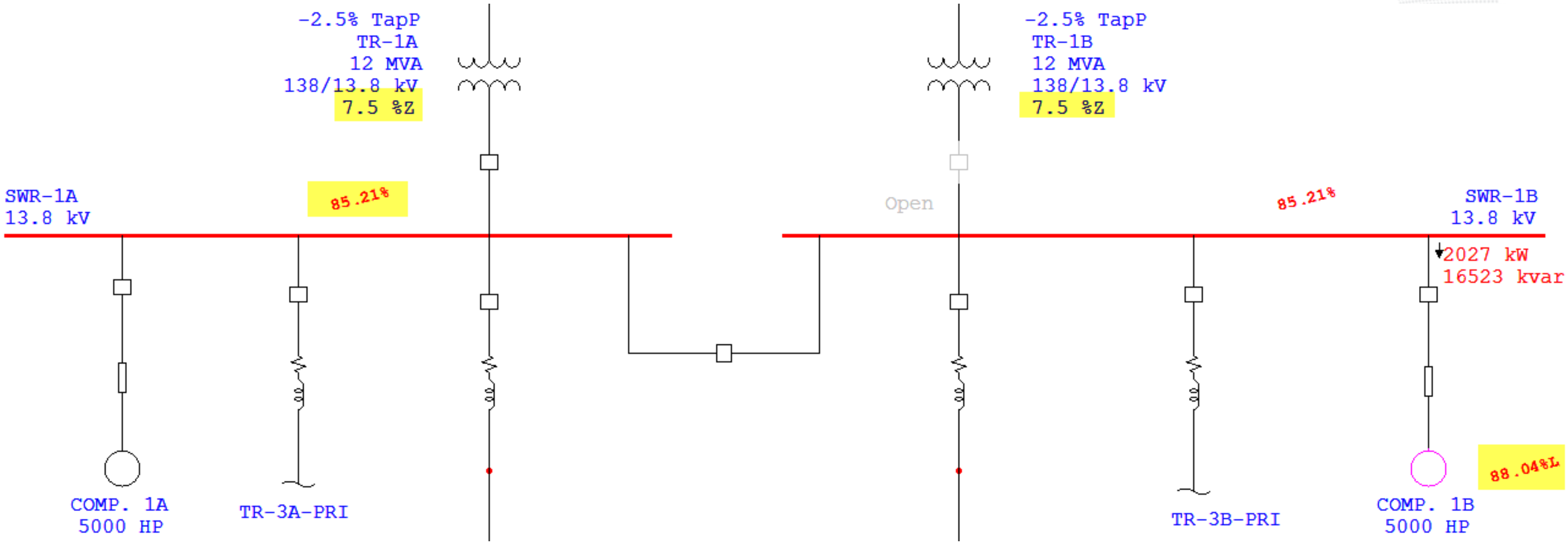
Starting standby 5000 hp, 13.2 kV motor – LRC changed to 500%



- The main and other switchgear buses are now above 80%, but is still marginal for FEED.
- Options include: lower transformer impedance, increase transformer size, include reduced-voltage starting.

Motor Starting Studies – 13.2 kV Motor Example

Starting standby 5000 hp, 13.2 kV motor, 500% LRC – chg Z to 7.5%



- Changing the transformer impedance should be cheaper than increasing the transformer size or adding a reduced-voltage starter.
- Must still confirm that switchgear is adequately rated for the increase in short-circuit.

Motor Starting Studies – Take-Aways

Things to remember

- Motors can be specified with reduced inrush currents if necessary.
- Transformers can be specified with lower impedances to improve regulation during motor starting.
- Fan-cooling adds capacity but does not affect motor starting capability.
- Larger base-rated transformers improve motor starting capability.
- Adjusting transformer taps will increase the normal operating voltage on a bus thus improving motor starting capability.

Short-Circuit Studies

Short-Circuit Studies – Types of Faults

- Three-Phase Fault (LLL or LLLG)
  - All three phases shorted together and may or may not involve ground
  - Typically is the only short-circuit analysis required because it is the most severe (in most cases)
- Single Line to Ground Fault (LG)
  - Any one phase shorted to ground
  - Only needs to be considered where a single-phase to ground fault might be higher than a three-phase fault. This can occur for faults near solidly grounded synchronous machines or solidly grounded wye sides of delta-wye transformers.
  - Since most industrial systems are typically low-resistance grounded or high-resistance grounded this analysis is not required.
- Line to Line Faults (LL or LLG)
  - Any two phases shorted together and may or may not include ground
  - May only be required for protective device coordination

Short-Circuit Studies – Study Factors

What factors need to be considered for short-circuit studies??

- Worst-case conditions
  - To minimize the number of cases required, consider only worst-case conditions.
  - For utility-fed systems typically consider the maximum MVA_{sc} , representing the minimum utility source impedance.
  - For generator-fed systems use the maximum number of units that may be online.
  - For double-ended systems with normally open ties, determine if the temporary parallel-source condition during a maintenance transfer will be considered.
  - When the maintenance transfer condition is not considered, single-end substations so that all motor contribution taken into account.
  - When applicable, include essential generators being exercised.
  - Use an applicable pre-fault voltage.
- Lumped Loads
  - Assume all constant-kVA if actual mix is unknown.

Short-Circuit Studies – Study Factors

What factors need to be considered for short-circuit studies?

- System impedances
  - Cables can be omitted for conservative results.
- Manufacturing tolerances
  - Since tested impedances are not available for grass-root FEED studies the maximum negative manufacturing tolerances should be used.
  - Be sure you know what your study software does with entered tolerances.
- Calculation standards
  - Perform calculations based on the applicable IEEE or IEC standard.
  - IEEE switchgear and NEMA motor control are based on IEEE C37 and have differing X/R bases thus differing duty calculations.
  - IEC controlgear is based on IEC 60909.

Short-Circuit Studies – Paralleling Sources

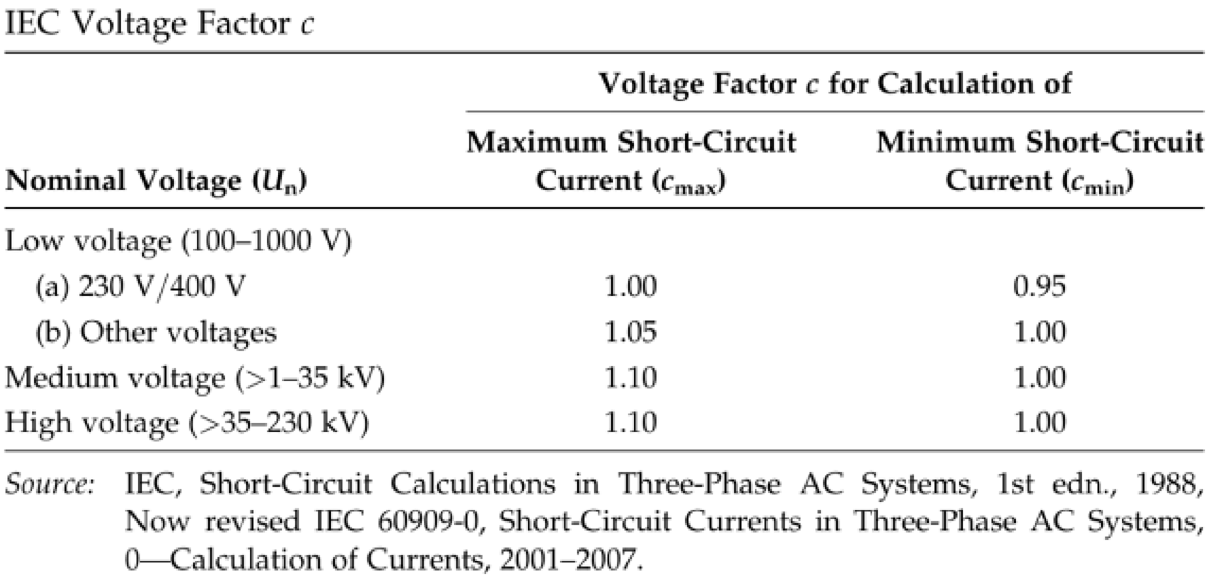
Do higher fault currents due to paralleling of sources during manual or automatic transfer need to be considered?

Per IEEE 666 – 2007, Section 4.6.1

“The major concern when paralleling both sources is fault current, which will be larger than that calculated for a single source. However, it is acceptable practice to design for the single-source condition if the duration of parallel operation is short.”

Short-Circuit Studies – Pre-Fault Voltage

- IEEE C37 Standards
  - Based on 100% pre-fault voltage
  - Higher and lower voltages are permissible depending on the operating conditions
- IEC 60909
  - Voltage factors (c-factors) are used to account for system loading that could result in higher pre-fault system voltages

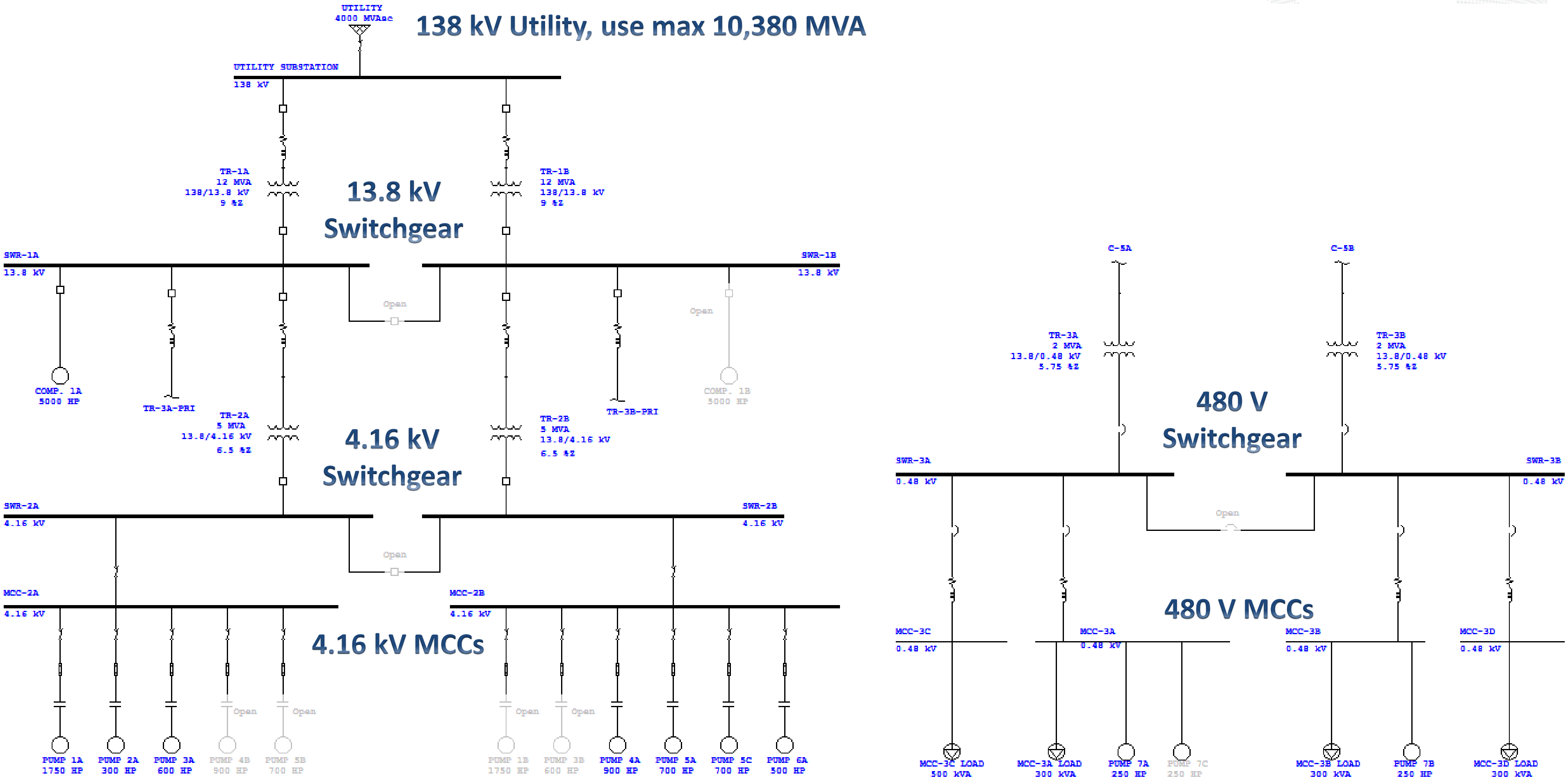


IEC Voltage Factor *c*

	Voltage Factor *c* for Calculation of	
Nominal Voltage (U_n)	**Maximum Short-Circuit Current ($c_{\max}$)**	**Minimum Short-Circuit Current ($c_{\min}$)**
Low voltage (100–1000 V)		
(a) 230 V/400 V	1.00	0.95
(b) Other voltages	1.05	1.00
Medium voltage (>1–35 kV)	1.10	1.00
High voltage (>35–230 kV)	1.10	1.00

Source: IEC, Short-Circuit Calculations in Three-Phase AC Systems, 1st edn., 1988, Now revised IEC 60909-0, Short-Circuit Currents in Three-Phase AC Systems, 0—Calculation of Currents, 2001–2007.

Short-Circuit Studies – Example System


138 kV Utility, use max 10,380 MVA

13.8 kV Switchgear

4.16 kV Switchgear

4.16 kV MCCs

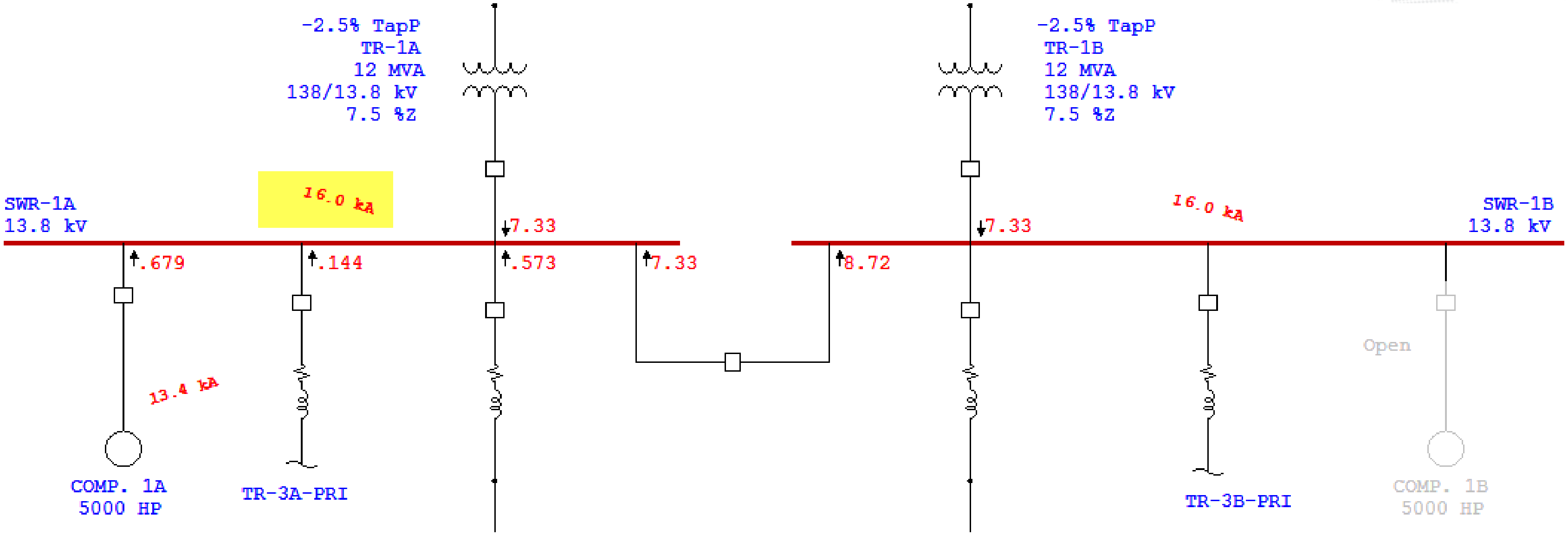
480 V Switchgear

480 V MCCs

We Deliver

Short-Circuit Studies – 13.8 kV Switchgear

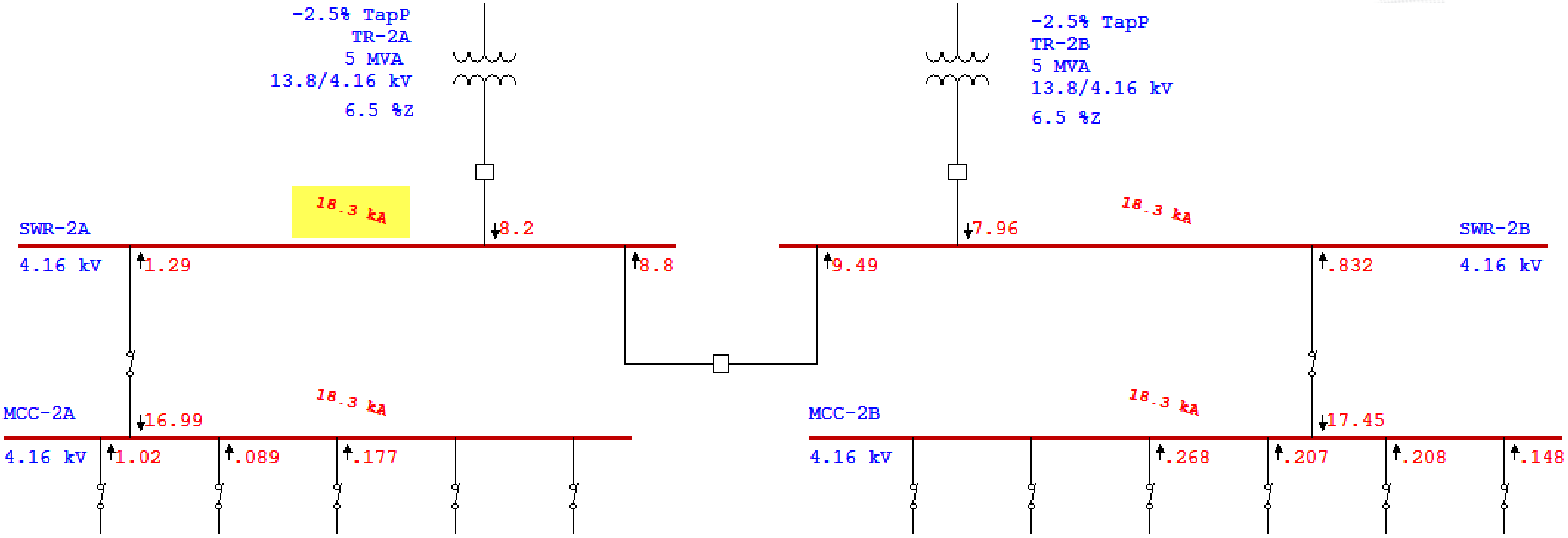
Closed-tie conditions for fully rated gear



- The 16.0 kA displayed is symmetrical (3-5 cycle) interrupting rms.
- The corresponding breaker momentary peak and adjusted interrupting duties are 44.5 kA and 16.5 kA, respectively.
- This is well below the minimum capabilities of 15 kV, 20 kA rated breakers – xxx kA peak and xx kA interrupting.
- Accordingly, a lower transformer Z could be used and the equipment rating bumped up to 25 kA rated gear.

Short-Circuit Studies – 4.16 kV System

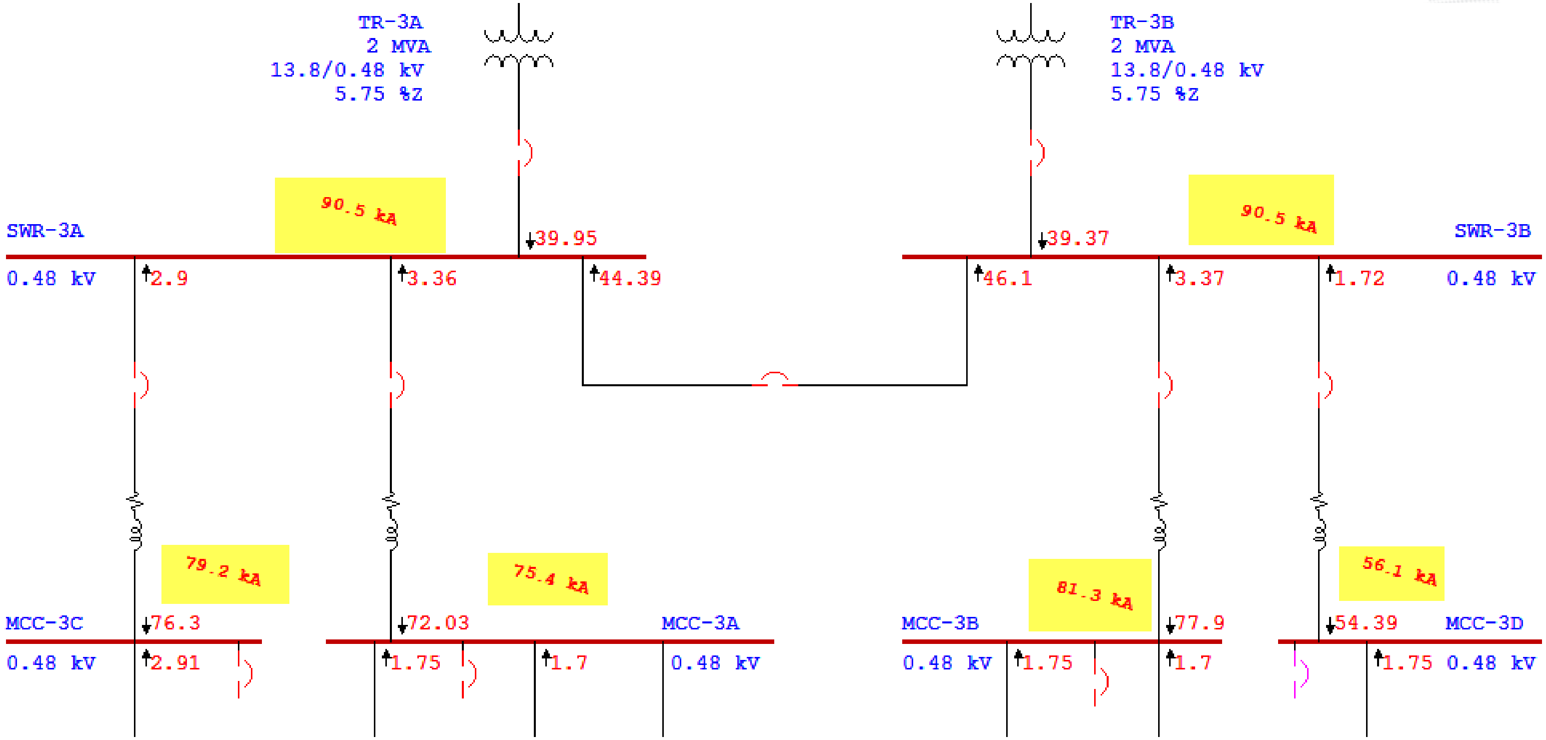
Closed-tie conditions for fully rated gear



- The 18.3 kA displayed is symmetrical (3-5 cycle) interrupting rms.
- The corresponding breaker momentary peak and adjusted sym. interrupting duties are 53.1 kA and 18.3 kA, respectively.
- The corresponding MCC sym. interrupting duty is 20.6 kA sym rms.
- All duties are well below the minimum capabilities of 5 kV, 31.5 kA switchgear and 50 kA MCC equipment.

Short-Circuit Studies – 480 V System

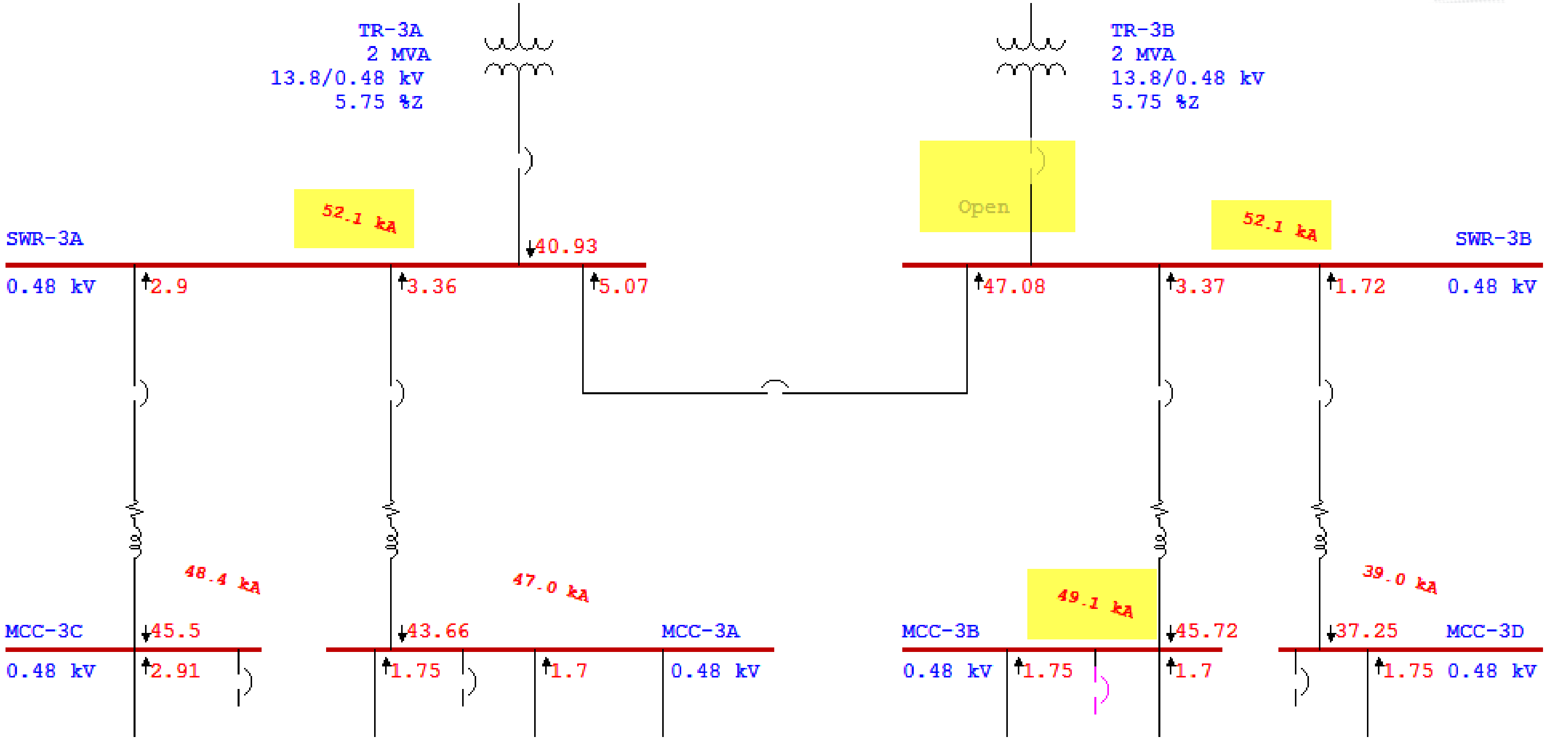
Closed-tie conditions for fully rated gear



- All values displayed are symmetrical (1/2-cycle) interrupting rms.
- Fully rating the gear for the maintenance transfer would require 100 kA switchgear and at least 85 kA MCCs. Typical 65 kA equipment would not be adequate.

Short-Circuit Studies – 480 V System

Single-ended conditions



- All values displayed are symmetrical (1/2-cycle) interrupting rms.
- If considering only single-ended conditions, 65 kA equipment would be adequately rated.

Short-Circuit Studies – Take-Aways

Things to remember

- Double-ended systems may or may not be fully rated for the temporary parallel source conditions during a maintenance transfer.
- If the system is small enough, minimum rated equipment may be adequate for both the single-ended and parallel source conditions.
- When higher rated gear is available, larger transformers and/or lower impedances can be entertained to improve motor starting capabilities.
- Make sure the calculations are conservative and leave a design margin in place to allow for load growth during detailed design or the addition of future loads.

Overcurrent Coordination Studies

Overcurrent Coordination Studies

Why do a preliminary coordination study?

- To demonstrate desired protection schemes and preferred coordination time intervals (CTIs).
- To identify protection zones and anticipated clearing using preferred CTIs.
- To identify clearing times to be used for preliminary arc-flash studies.
- To identify relay types and functionality required for the various equipment types.
- To assess if min SC case has adequate current levels to operate protection.

Overcurrent Coordination Studies

What early data is needed? What can be the impact?

- Types of overcurrent relays and other protective devices
    - Actual model numbers and available functions are best

Arc-Flash Studies

Arc-Flash Studies

Why do a preliminary arc-flash study?

- To determine maximum incident energy (IE) exposures using passive and/or active protection schemes.
- To address IE levels over the NFPA maximum of 40 cal/cm^2 and/or lower client-required limits.
- To identify relay types and functionality required for the various equipment types.

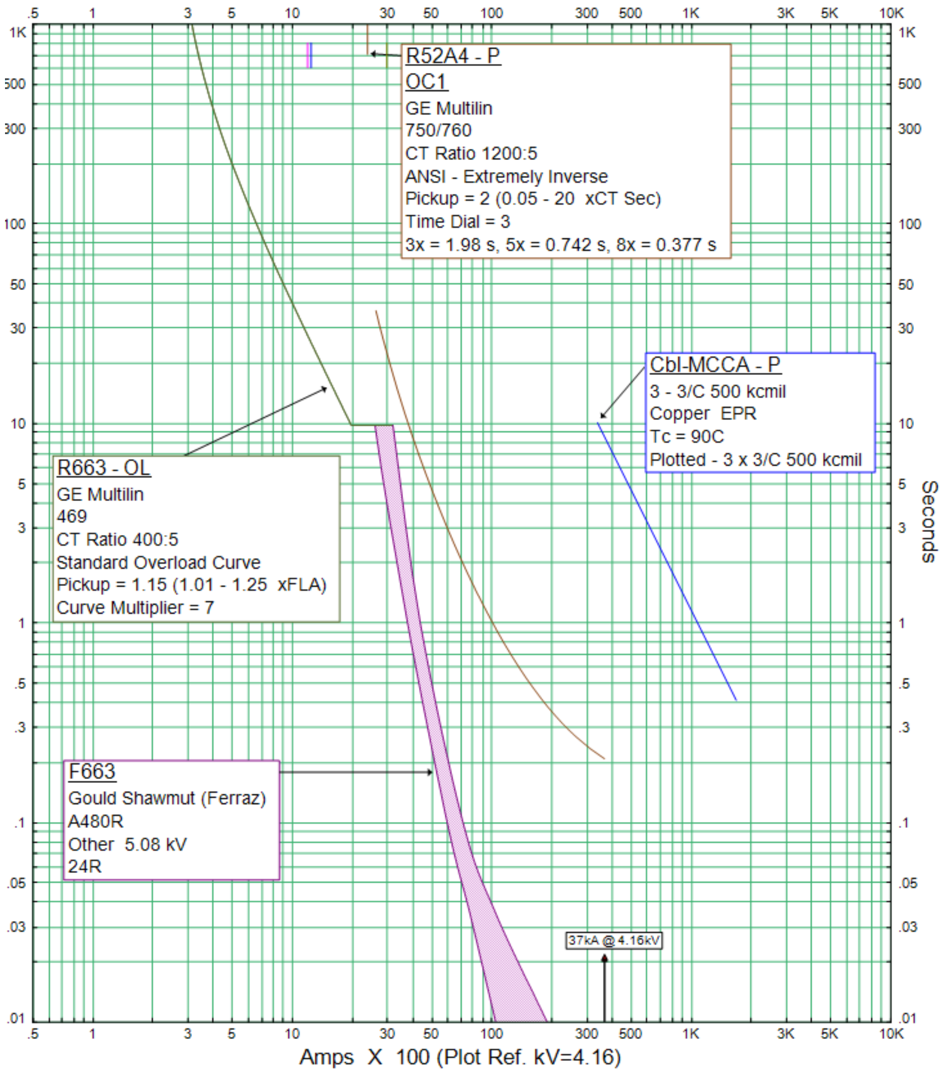
Arc-Flash Studies

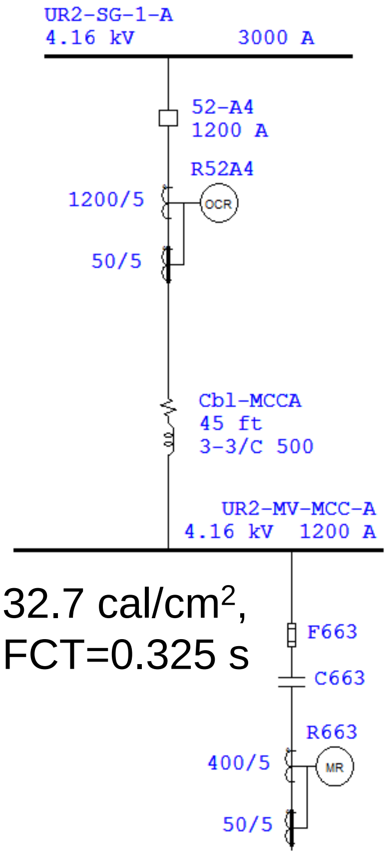
What early data is needed? What can be the impact?

- Types of overcurrent relays and other protective devices
  - Actual model numbers and available functions are best
- Incident energy (IE) limits
  - NFPA 70E limit of 40 cal/cm^2 is default upper limit
  - Many clients now want to limit the IE to the rating of standard fire-resistant clothing (FRC) with an ATPV of 8 cal/cm^2
- Can require changes to:
  - Relay model numbers (additional OC elements, setting groups, contact I/O)
  - Use of maintenance mode protection (for faster clearing)
  - MV breaker speed (5-cycle vs. 3-cycle)
  - Transformer impedances (to limit SC current)

Arc-Flash Studies

MV MCC example – w/traditional coordination & 5-cycle breaker

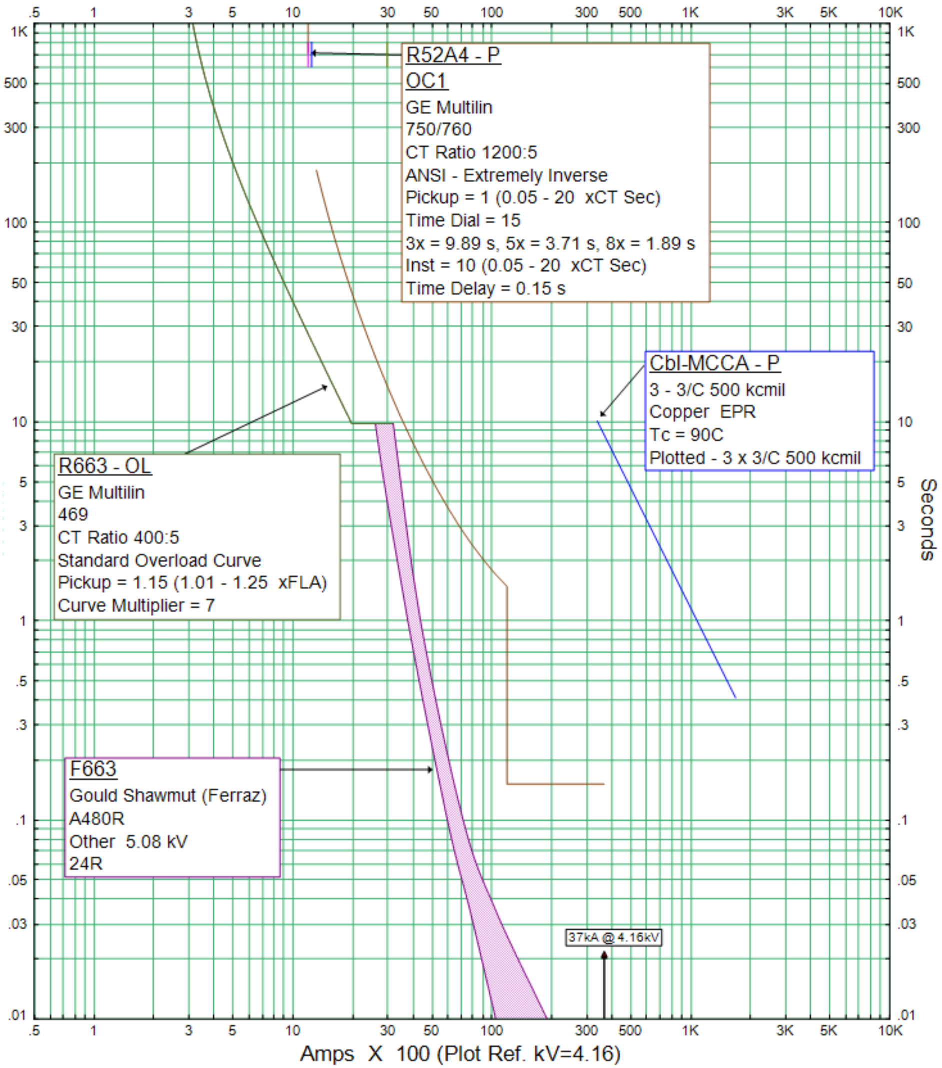


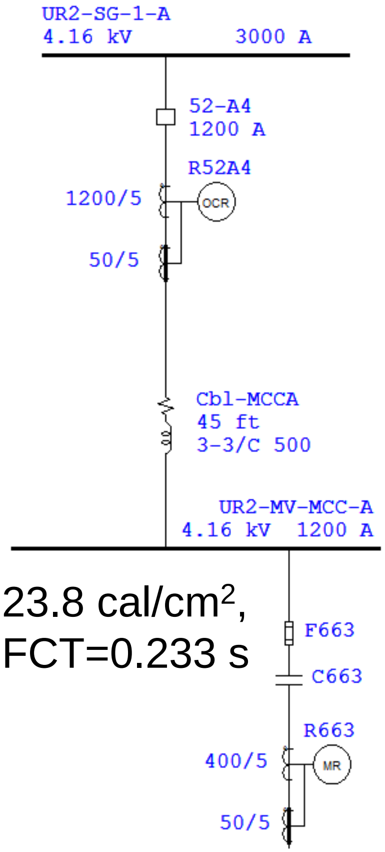


32.7 cal/cm^2,
FCT=0.325 s

Arc-Flash Studies

MV MCC example – w/additional OC element & 5-cycle breaker

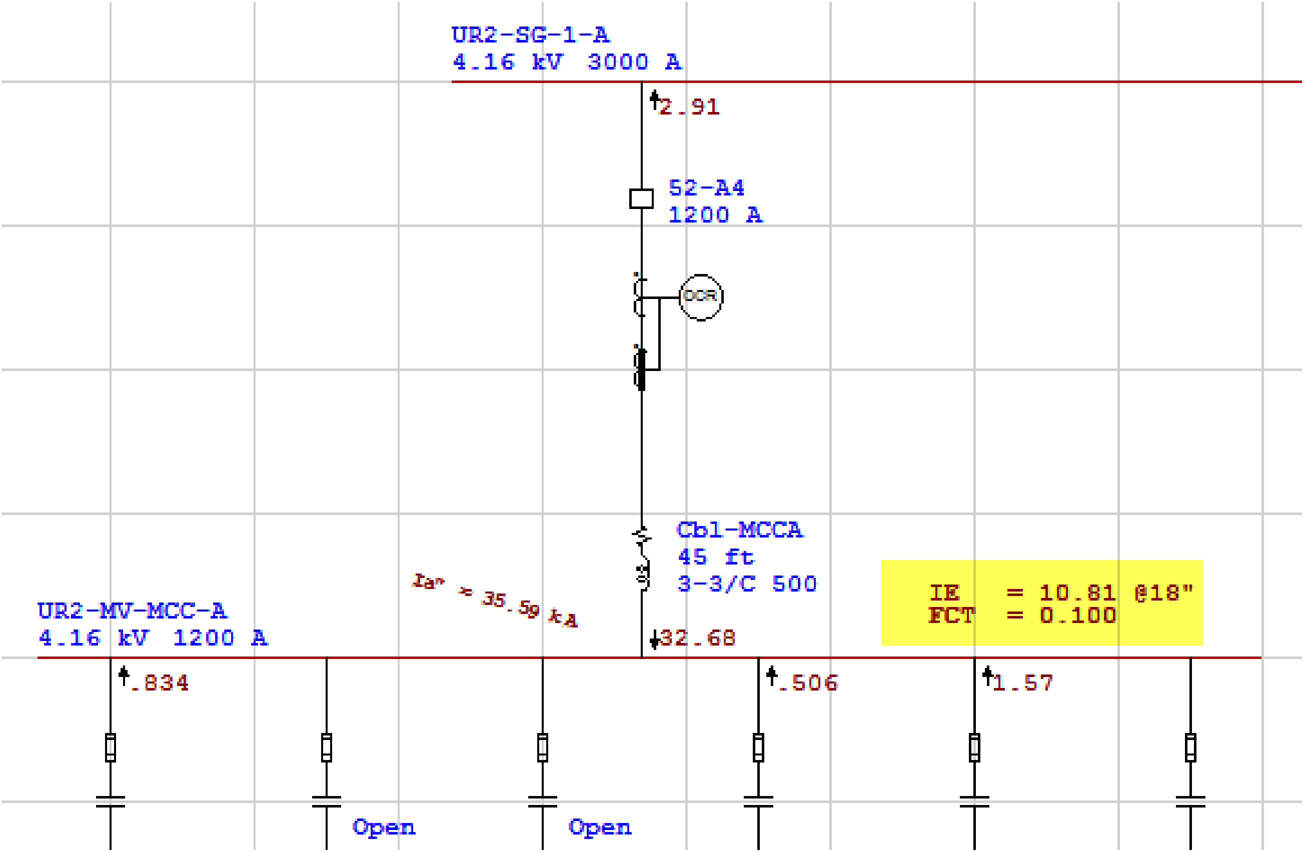




23.8 cal/cm^2,
FCT=0.233 s

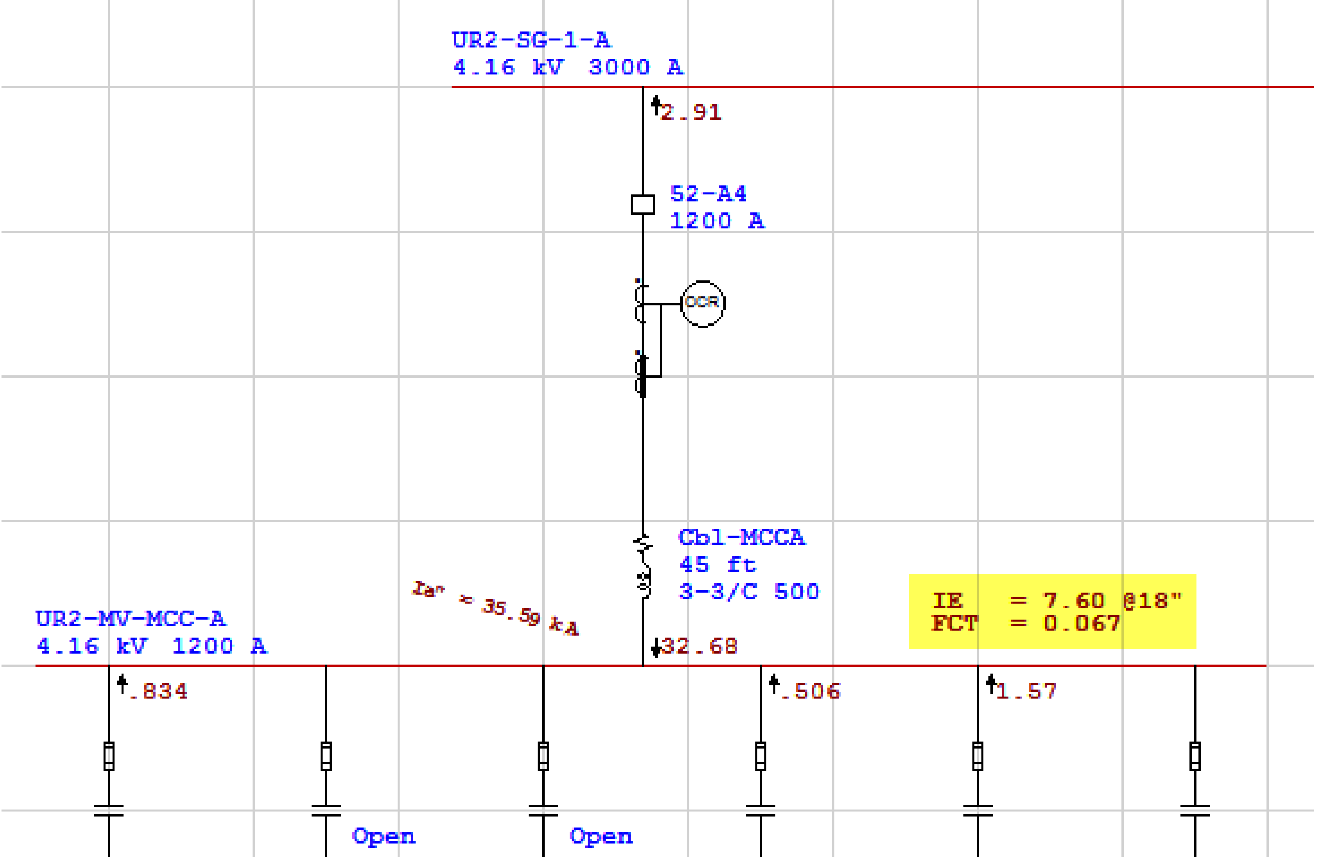
Arc-Flash Studies

MV MCC example – maintenance mode & 5-cycle breaker



Arc-Flash Studies

MV MCC example – maintenance mode & 3-cycle breaker



Harmonic Studies

Harmonic Studies

Why do a preliminary harmonic study?

- If there are one or several large MV drives to be installed. Study can help identify need for higher-pulse drives and/or filtering.
- If there is a large percentage of non-linear load to be installed at a single substation, typically over 25%.
- If there are drives added to a system with existing or new power factor capacitor banks. Study can identify if harmonic resonance issues may occur.

Harmonic Studies

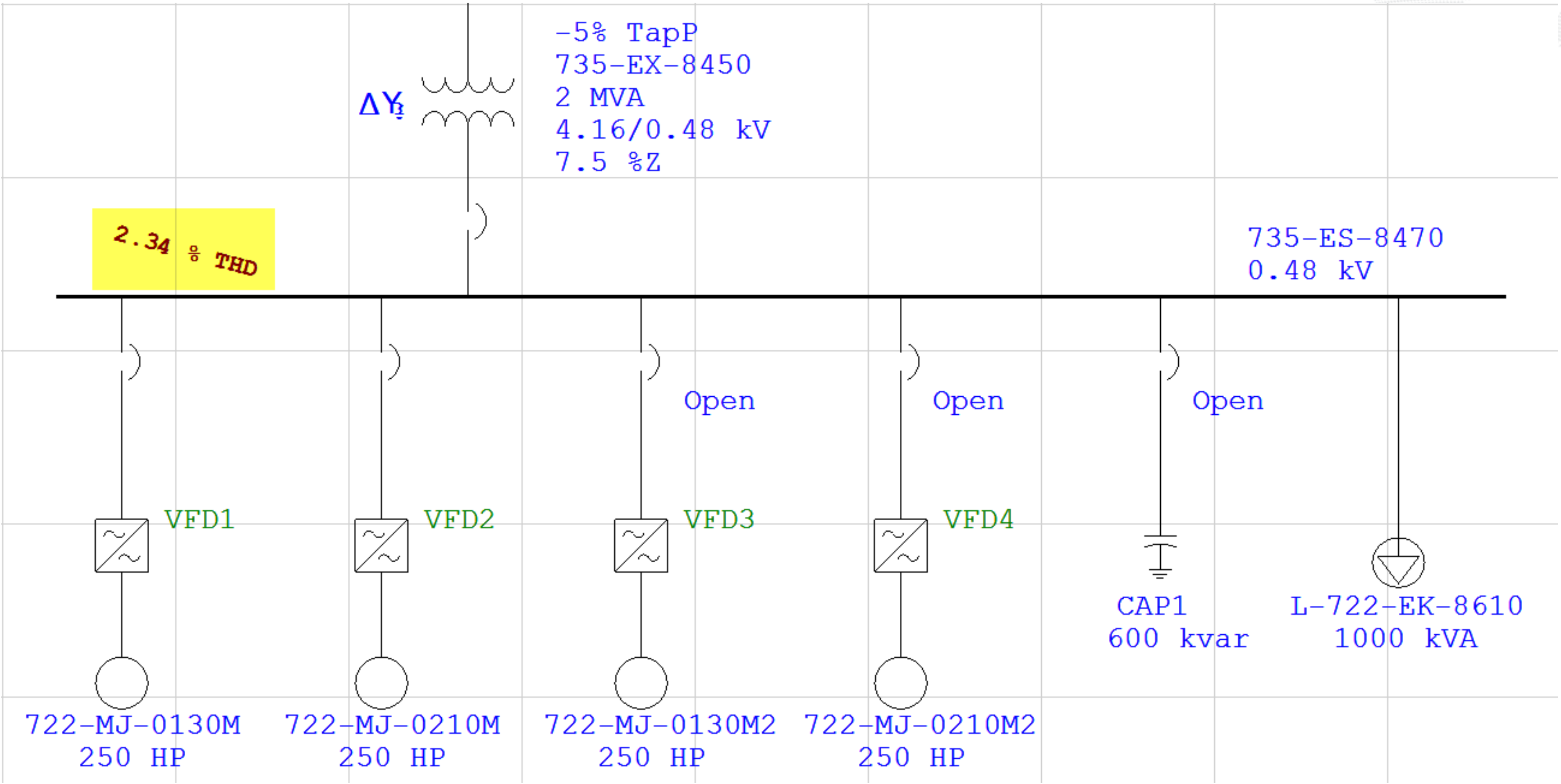
What early data is needed? What can be the impact?

- Types of drives being used
  - Six-pulse, 12-pulse, etc.
  - Supplier-specific harmonic spectrum if possible
- Capacitor bank ratings, if applicable
  - Cap banks cause a parallel resonance point that may exacerbate voltage distortion
- Can require changes to:
  - Drive topology, filtering
  - Transformer impedances
  - Cap bank tuning

Harmonic Studies

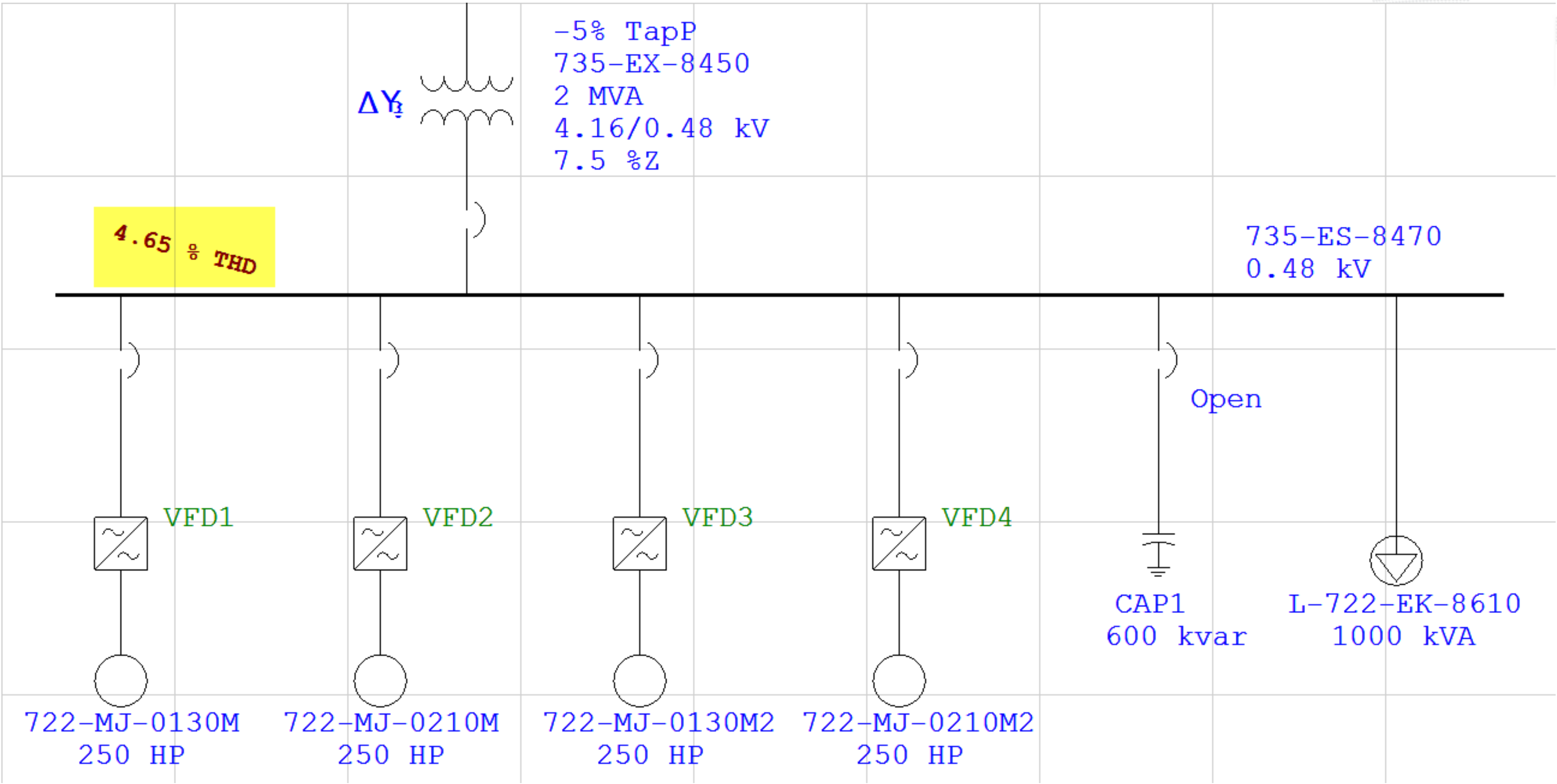
Engineering & Construction

LV bus example – two large six-pulse drives, w/o cap bank



Harmonic Studies

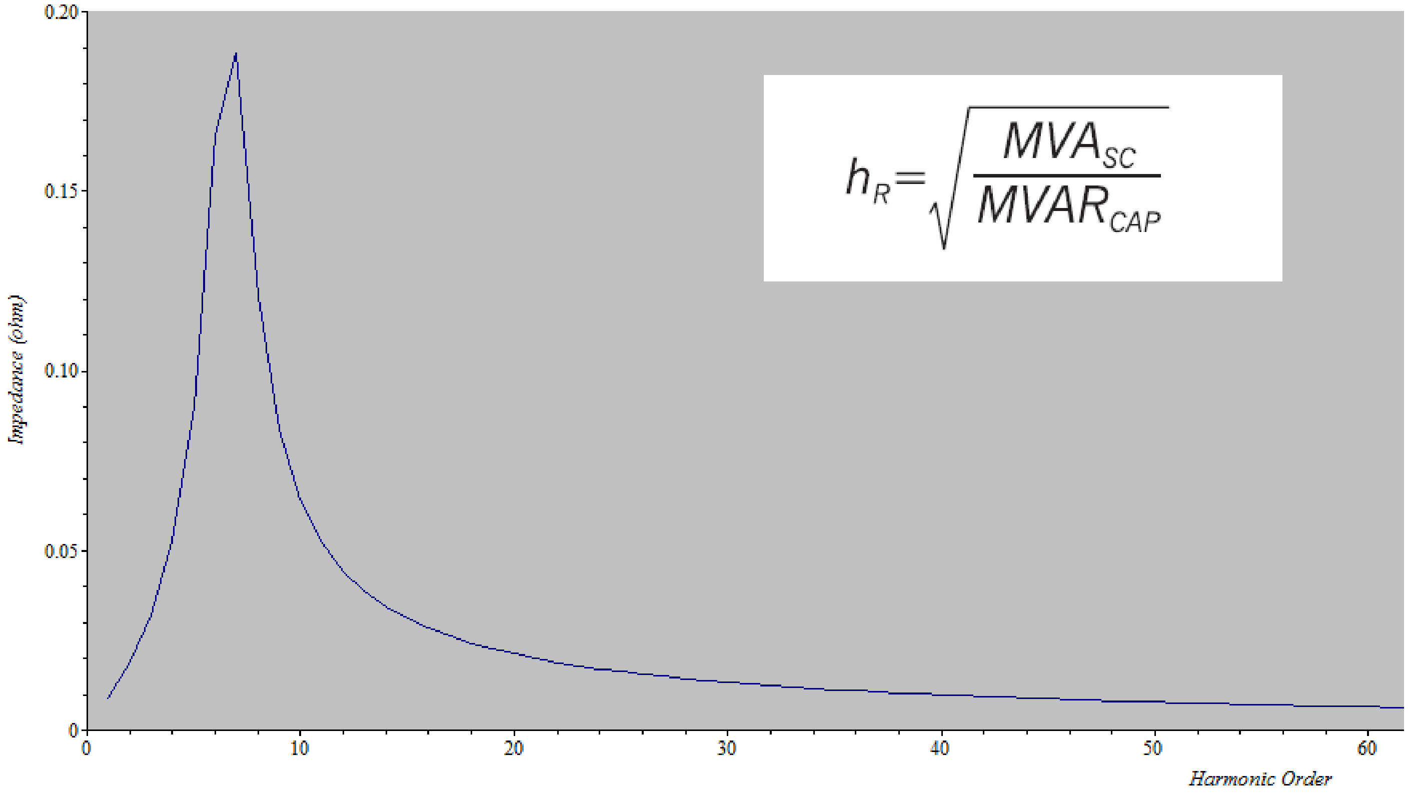
LV bus example – four large six-pulse drives, w/o cap bank



Harmonic Studies

LV bus example – capacitor banks & resonance

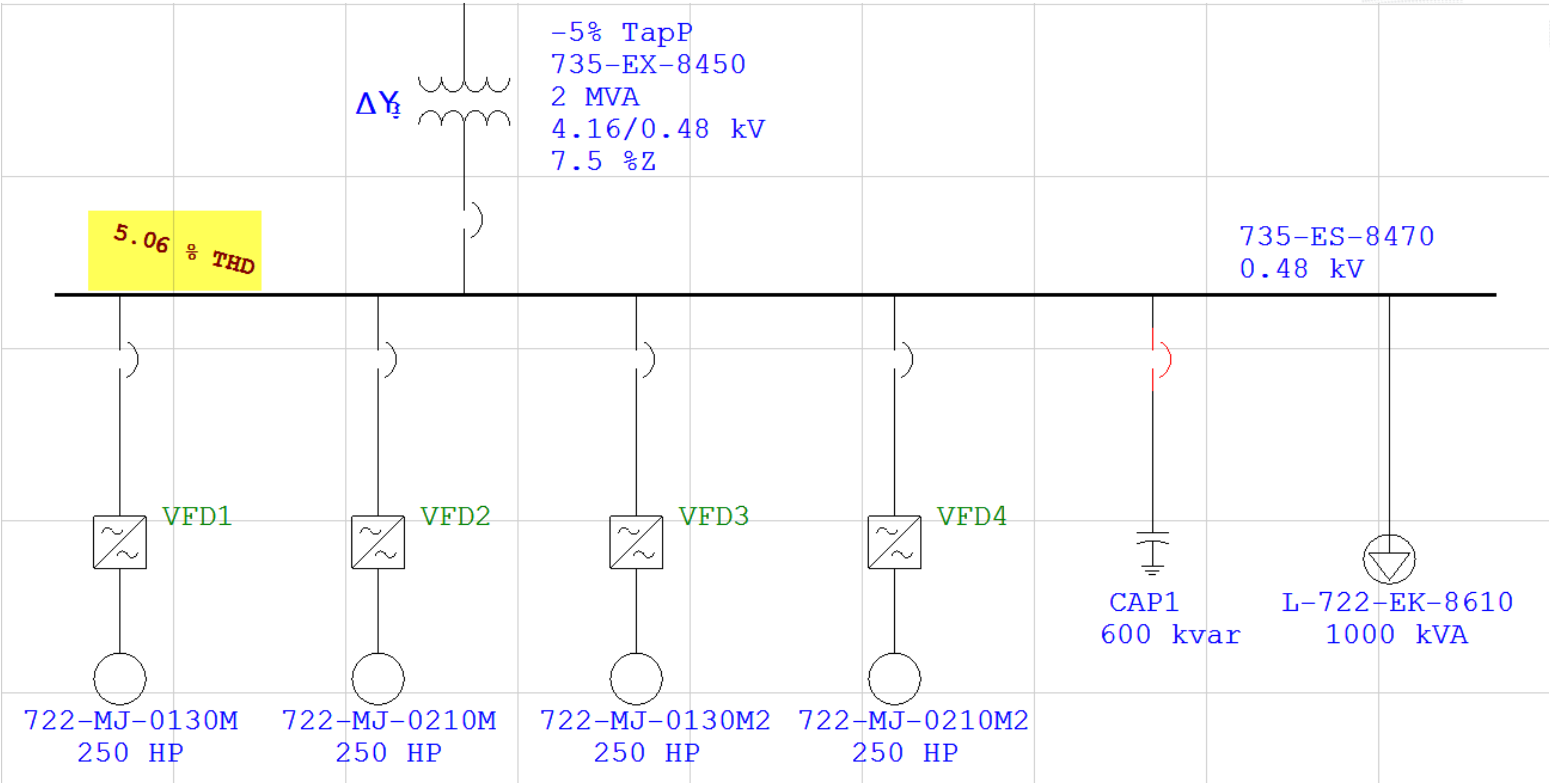
Frequency scan with cap bank



$$h_R = \sqrt{\frac{MVA_{SC}}{MVAR_{CAP}}}$$

Harmonic Studies

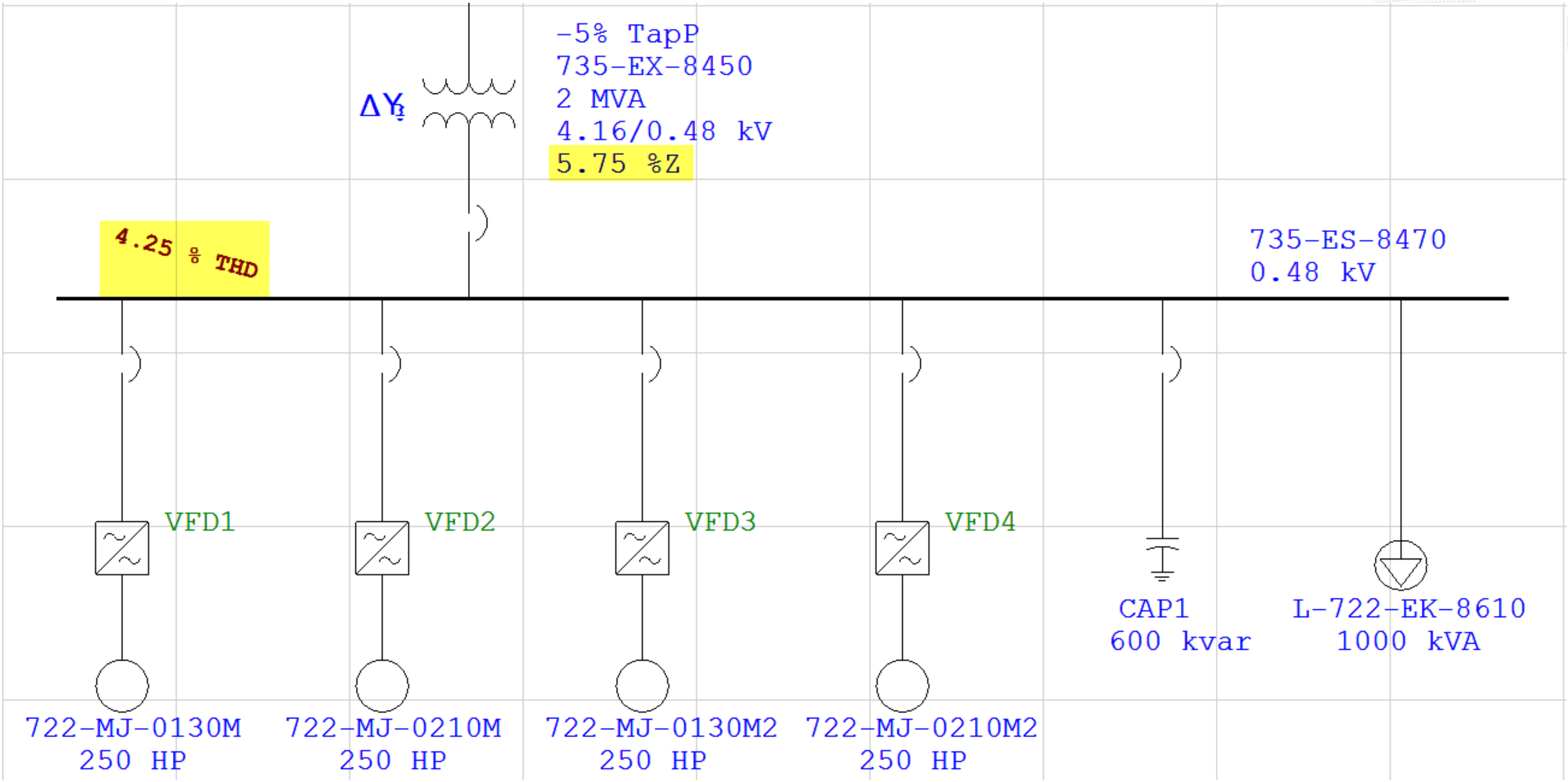
LV bus example – four large drives with capacitor bank



Harmonic Studies

Engineering & Construction

LV bus example – four large drives, capacitor bank, & lower Z%



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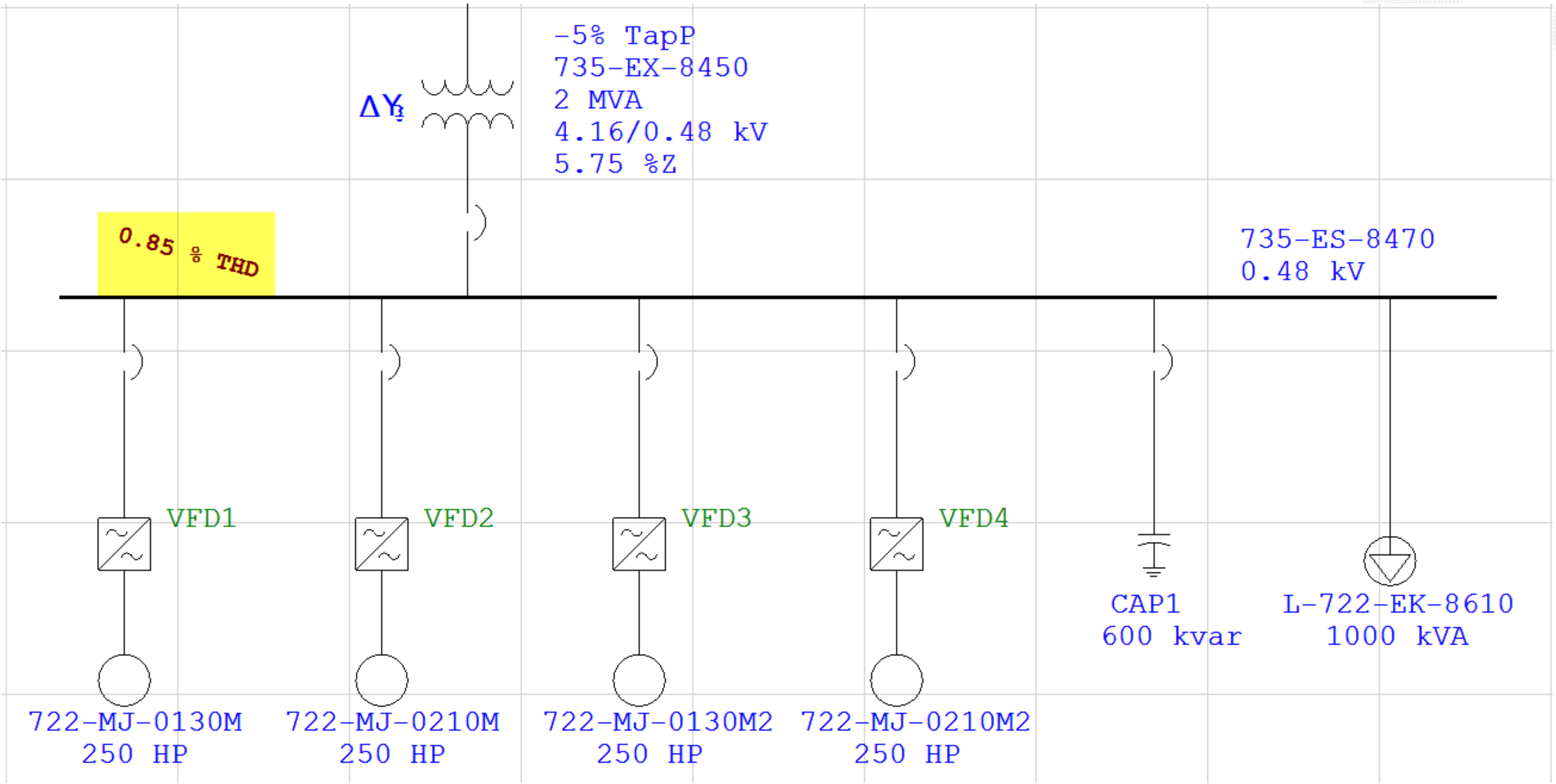
ZERO HARM courage to care

Harmonic Studies

Engineering & Construction

LV bus example – changing to 12-pulse drives



KBR We Deliver

ZERO HARM courage to care

Transient Stability Studies

Transient Stability Studies

Why do a preliminary transient stability study?

- Because the client requires it?
- Identify information needs to require from suppliers.
- Evaluate impedances of major equipment between generators and utility.

Transient Stability Studies

What early data is needed? What can be the impact?

- Dynamic data for synchronous machines
  - Impedances and time constants
  - Governor and voltage regulator models

- Type of cases to consider
  - Step load addition, such as the loss of a generator
  - Step load addition, such as starting of a large motor
  - Step load rejection, such as tripping of a large load
  - Operation of fast load shedding
  - Operation of underfrequency load shedding
  - Critical clearing time for faults

- Can require changes to:
  - Generator unit transformer and/or utility transformer impedances. Affects critical clearing time before units pull out of sync with utility.

Transient Stability Studies

For additional information…

- Refer to IEEE CED #375 on Stability Studies for Industrial Power Systems, 24-25 April, 2012

Extra LF Example

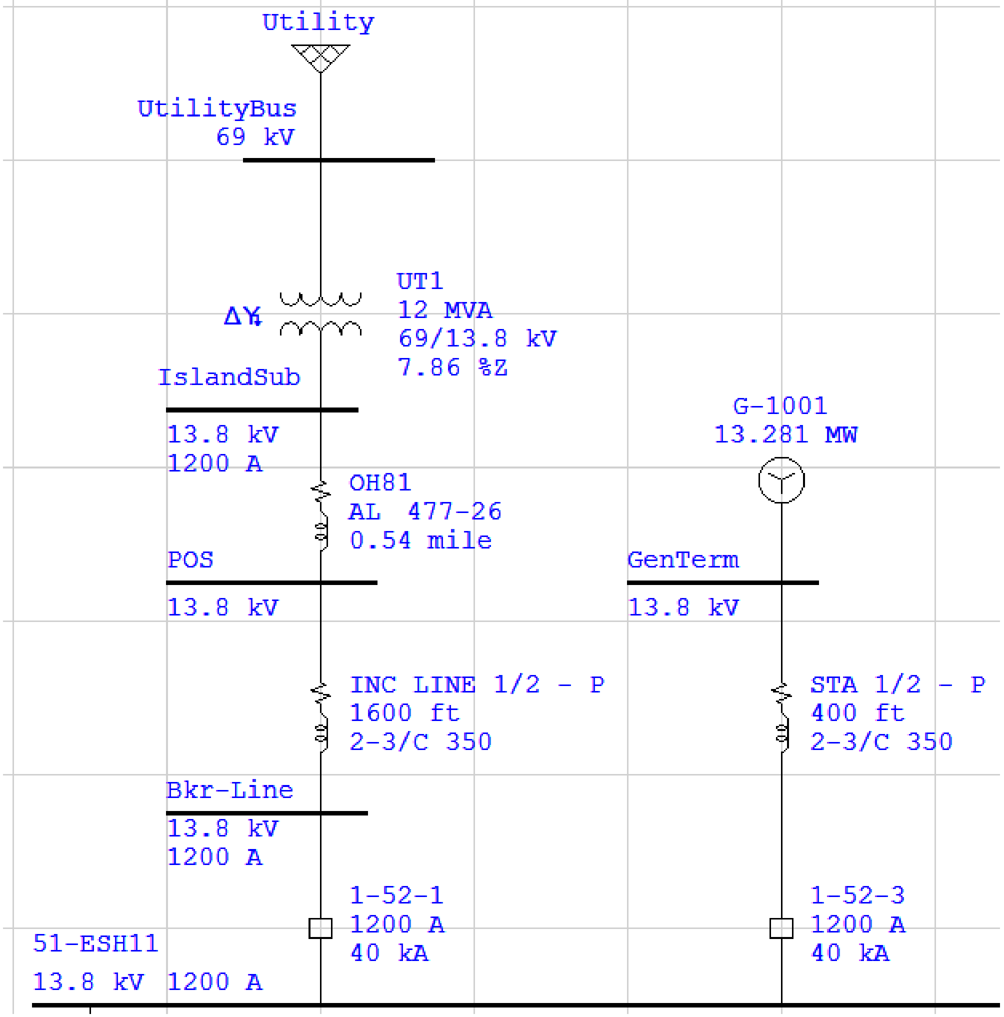
Load Flow Studies – Generator & Utility

Generator operating in parallel with utility

- Generators operating in parallel with utilities typically have their governors set in droop control.
- The level of output power depends on what is negotiated with the utility company.
- The automatic voltage regulator (AVR) can be set to operate in voltage control, reactive power control, or power factor control.

Load Flow Studies – Generator & Utility

Generator operating in parallel with utility

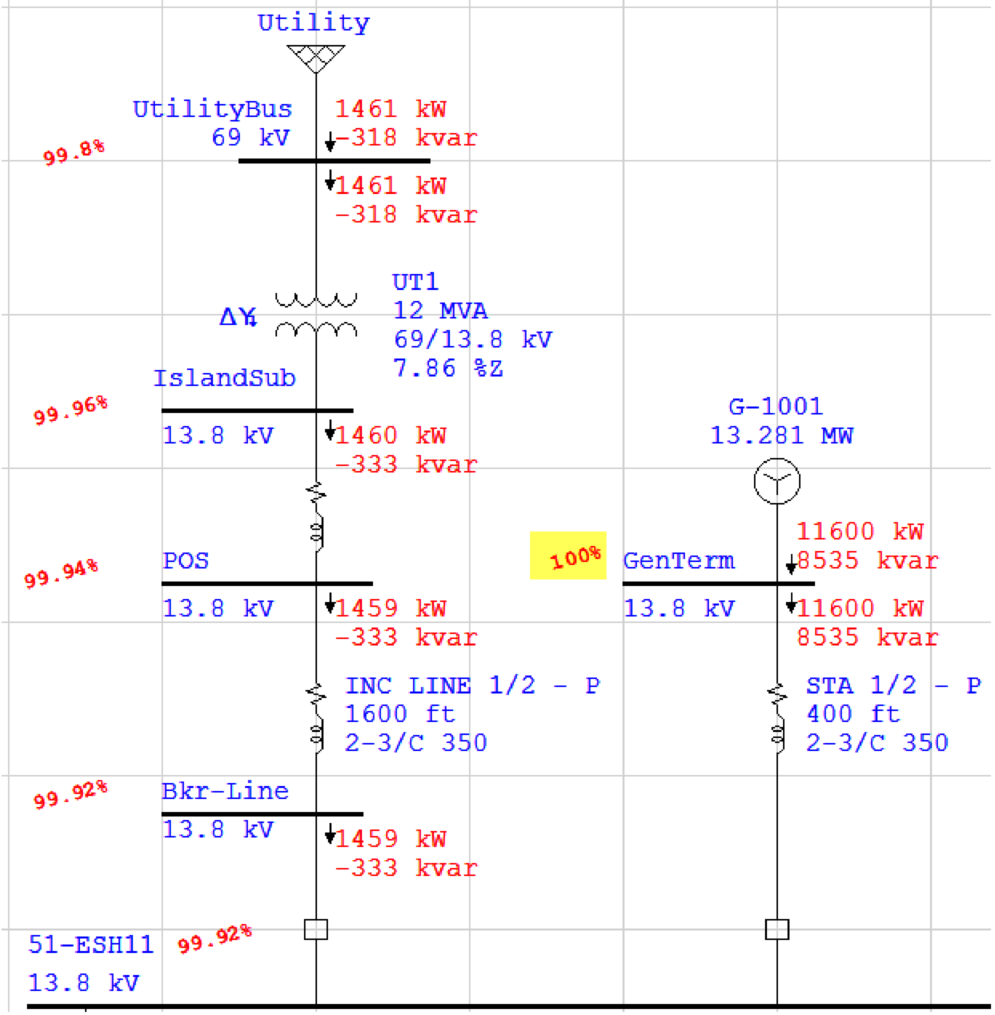


- For this system assume that generator provides 11.6 MW of the total 13.0 MW plant load.
- The utility voltage is nominally 99.8%.

Load Flow Studies – Generator & Utility

Engineering & Construction

Generator operating in parallel with utility



- With the utility transformer tapped at nominal and the generator AVR in voltage control at 100% there is an export of 333 kvar, a leading PF of 97.5%

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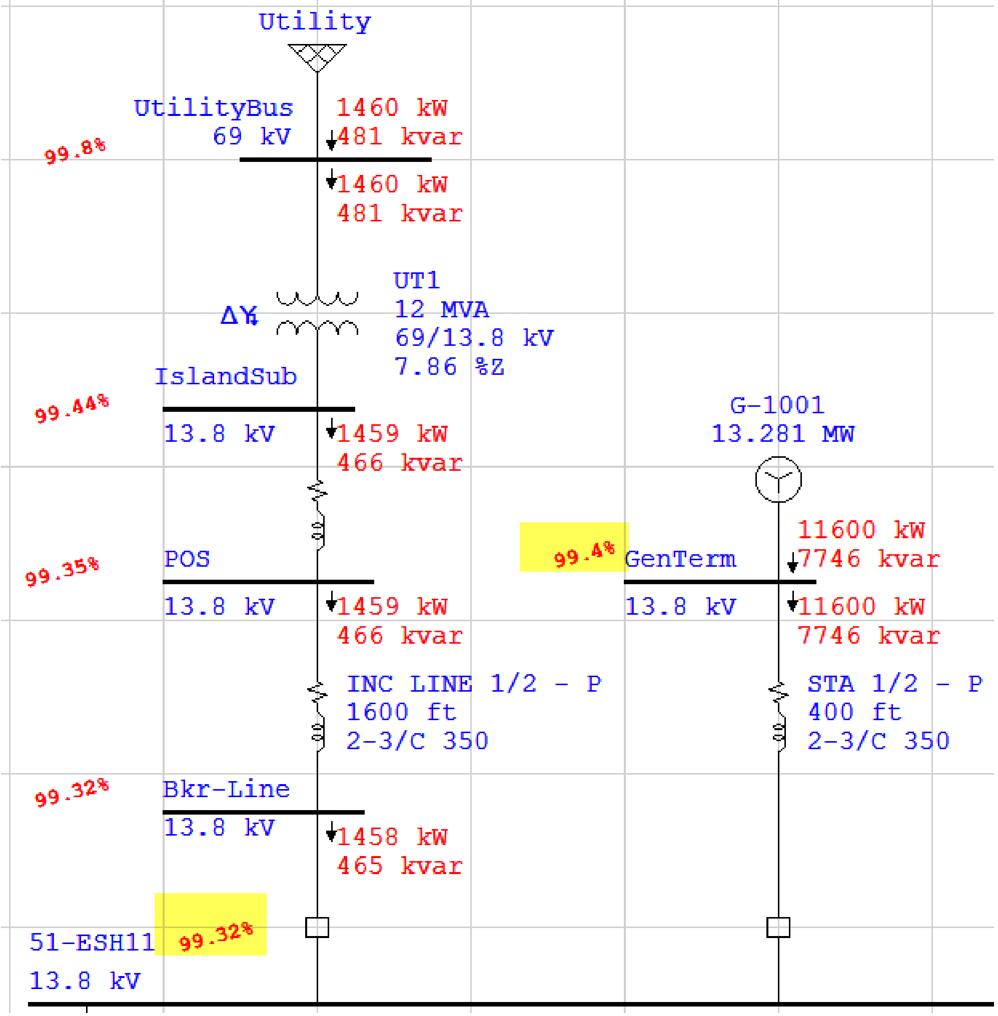
Load Flow Studies – Generator & Utility

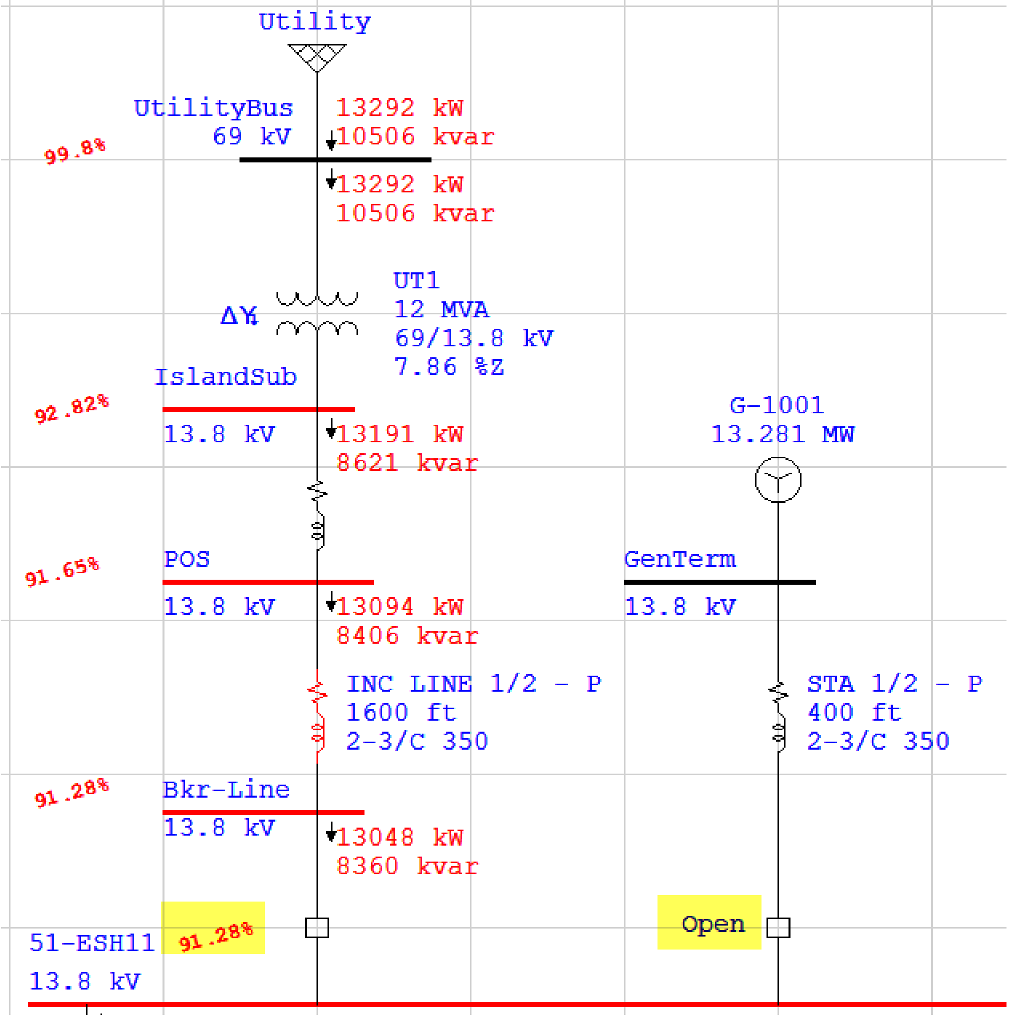
Generator operating in parallel with utility



- To achieve a lagging PF of approximately 95%, the AVR must be set to hold approximately 99.4%.
- The main bus voltage runs just a little below nominal at 99.3%.

Load Flow Studies – Generator & Utility

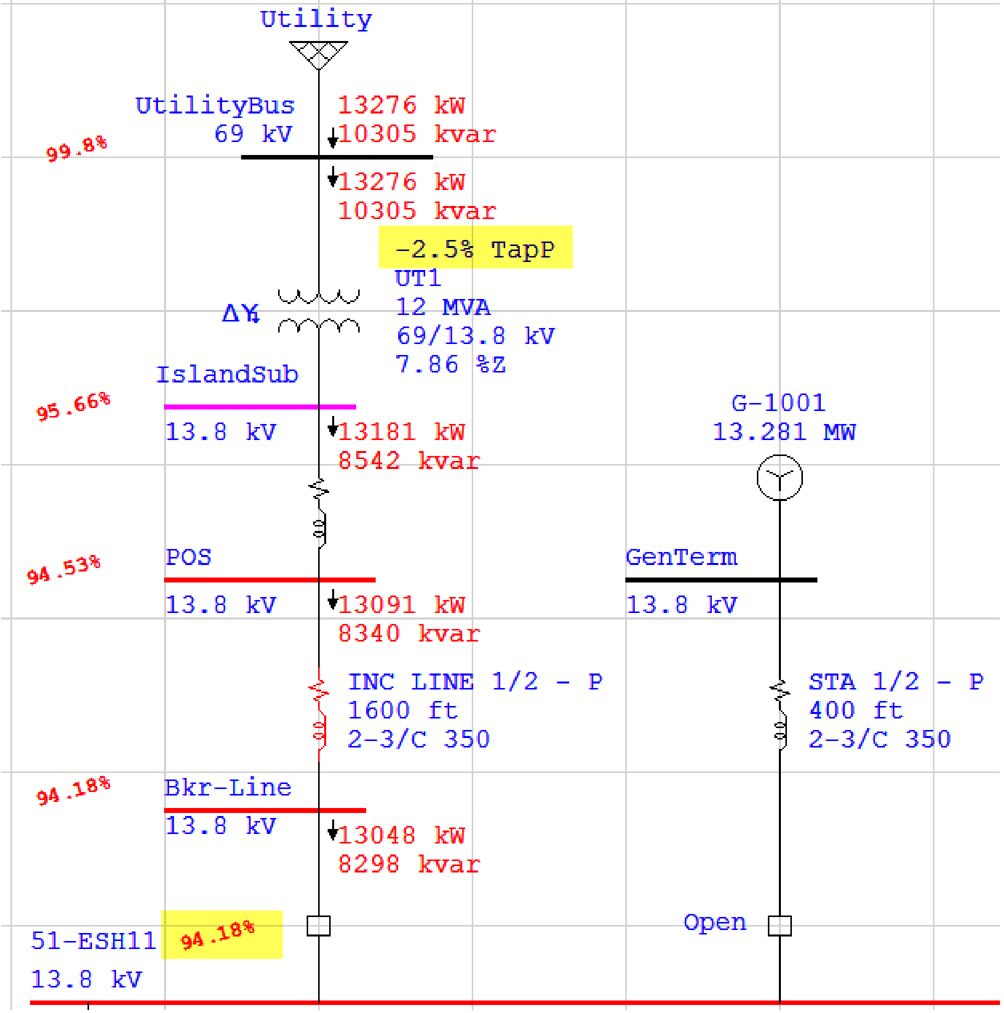
Generator operating in parallel with utility



- In the event of a generator trip all of the plant load is instantly supplied through the utility transformer.
- Due to the transformer impedance, the main bus voltage sags to 91.3%, even if the transformer includes a load tap changer (LTC).
- Without an LTC the generator cannot be re-synced to the utility without reducing plant load to increase the main bus voltage.

Load Flow Studies – Generator & Utility

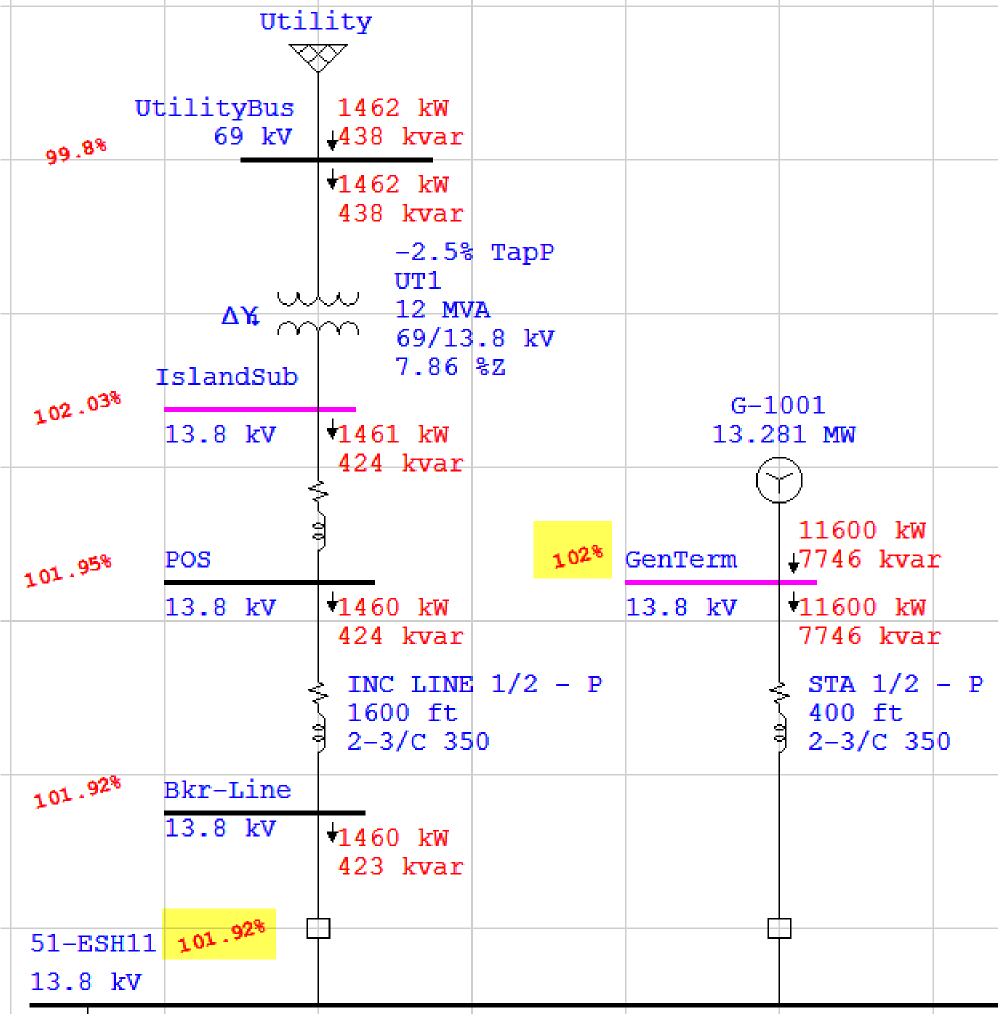
Generator operating in parallel with utility



- With the utility transformer tapped at -2.5% the main bus voltage rises to 94.2%.
- This is still a bit low for reconnecting the generator, but is more workable.

Load Flow Studies – Generator & Utility

Generator operating in parallel with utility



- To maintain close to 95% lagging PF, the generator AVR needs to hold approximately 102%
- The main bus voltage is slightly above nominal at 101.9%.

Extra MS Examples

Motor Starting Studies – Captive Transformers

Starting motor on a captive transformer

- Starting a large motor on a captive transformer isolates the voltage drop from the rest of the system.
- The size and impedance of the captive transformer is the primary variable in defining/determining the voltage drop.
- The minimum size depends on the starting kVA, frequency of starting, and pulsating loads if applicable (see IEEE papers).
- The transformer supplier must be advised of the application.

Motor Starting Studies – Captive Transformers

Starting motor on a captive transformer

- Since a starting motor is a constant impedance, lower voltages at the motor terminals result in less inrush and thus less voltage drop through the upstream impedances.
- Since the starting motor is isolated from the system, a lower motor terminal voltage such as 70% may be specified.
- If the application requires high starting torque the standard 80% minimum motor voltage may still be needed.

Motor Starting Studies – Impact on Utility

Starting motor on a captive transformer – impact on utility

- When starting very large motors such as those on captive transformers, the impact on the utility system must be considered.
- Utilities typically want to limit the change in system voltage (drop or rise) to between 1% to 3%.
- As an example, Centerpoint’s limit for a 138 kV substation on the Houston ship is:
  - 1.5% drop when operating with both utility lines in service
  - 2.0% drop with operating with one line out of service.

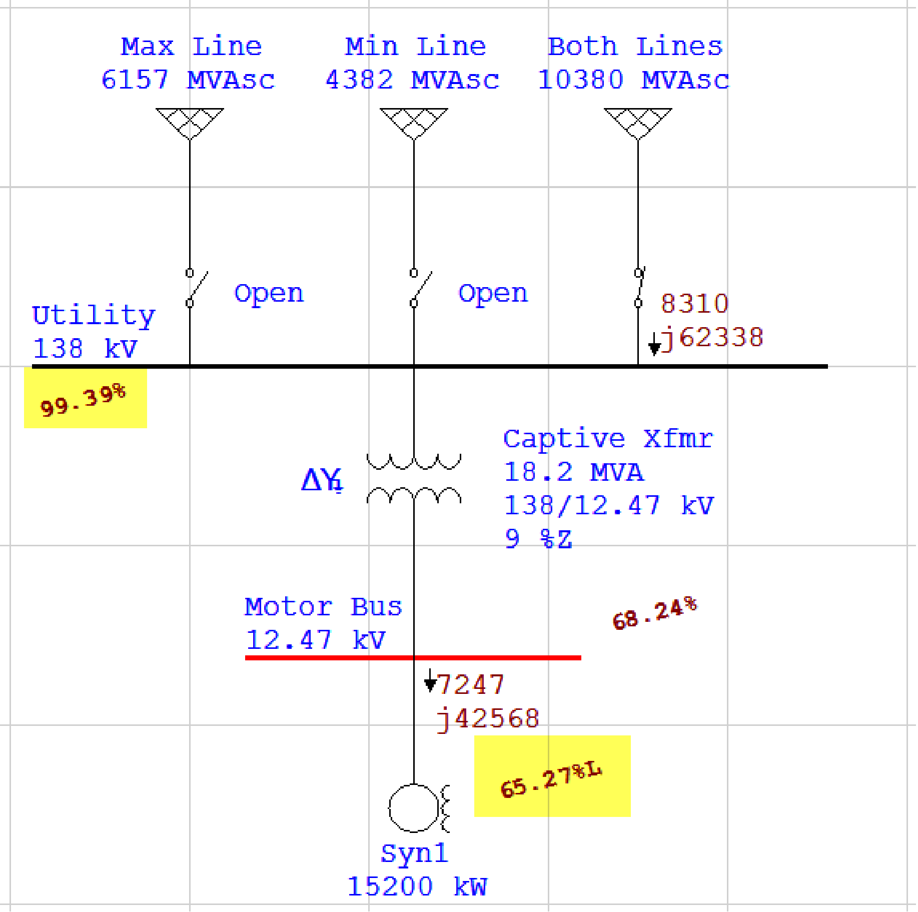
Motor Starting Studies – Captive Example

Starting motor on a captive transformer

- Consider starting a 15.2 MW, 0.8 PF motor (20,375 hp)
- Due to the application, a minimum terminal voltage of 80% is required.
- Begin assuming a typical sync motor inrush of 500%. Starting MVA = 96.9.
- Considering a maximum of two starts/hour and no pulsating loads, per an IEEE paper the minimum FA rating of the captive transformer is the Starting MVA / 4 = 24.2.
- The ONAN rating is 18.2 MVA with a standard impedance of 9%

Motor Starting Studies – Captive Example

Starting motor on a captive transformer - example

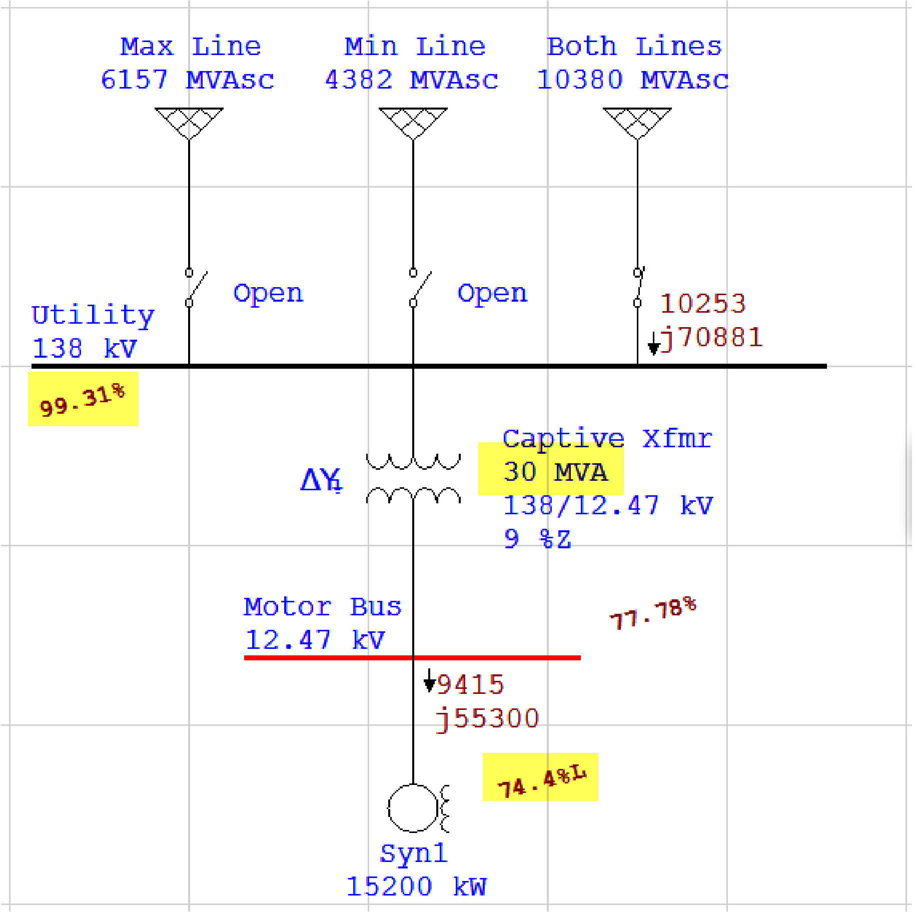


- Based on a utility pre-start voltage of 100% and both lines in service,
- With the captive transformer tapped at nominal,
- The voltage drop in the utility is 0.61% which is less than the 1.5% limit,
- But the motor terminal voltage of 68% is much too low.

→ Voltage drop can be shifted from the motor terminals to the utility. Start with increasing transformer size.

Motor Starting Studies – Captive Example

Starting motor on a captive transformer - example

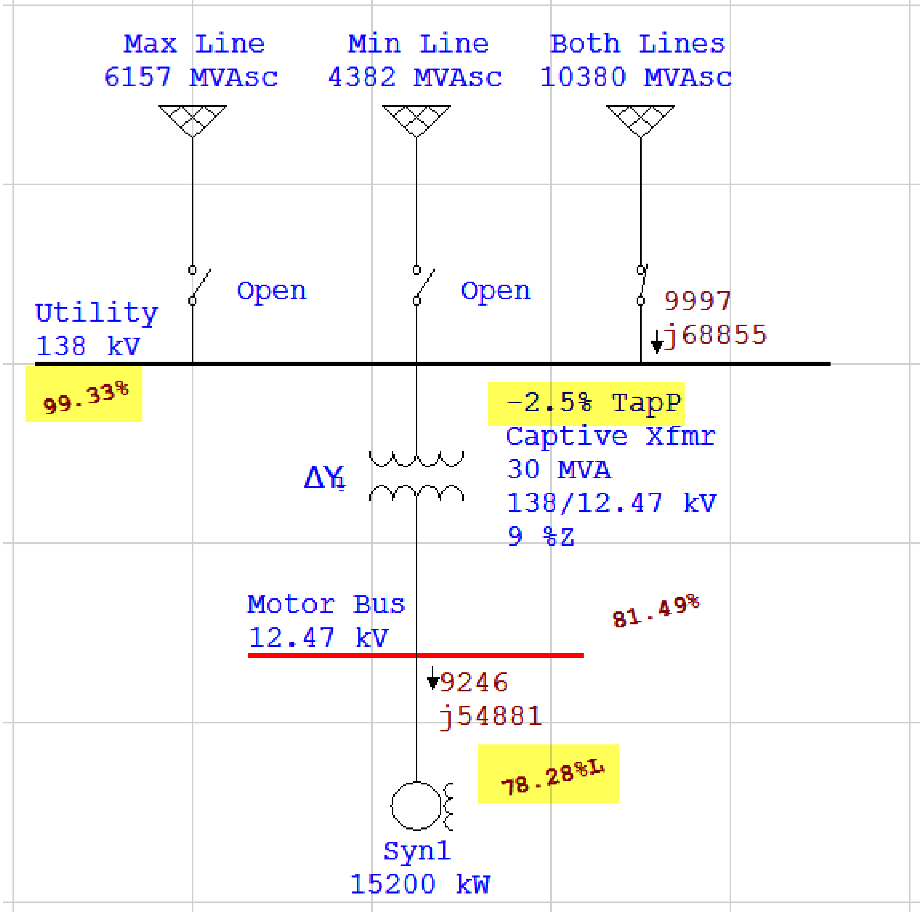


- Increasing the transformer to 30 MVA ONAN-only
- The voltage drop in the utility increases slightly to 0.69%.
- The motor terminal voltage increases to 74% but is still unacceptable.

→ Try adjusting the transformer tap to -2.5% and lowering the inrush to 450%.

Motor Starting Studies – Captive Example

Starting motor on a captive transformer - example

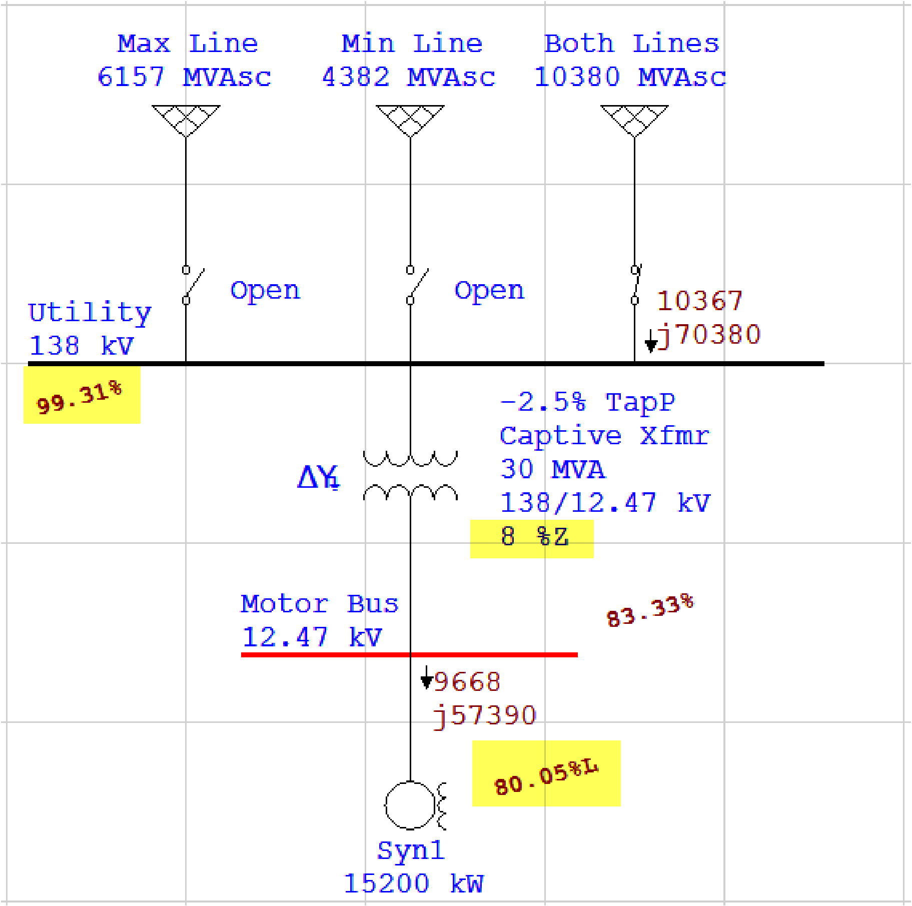


- The voltage drop in the utility reduces slightly to 0.67% due to the reduced inrush.
- The motor terminal voltage increases to 78.3% but is still unacceptable.

→ Try reducing the transformer impedance from the standard 9%.

Motor Starting Studies – Captive Example

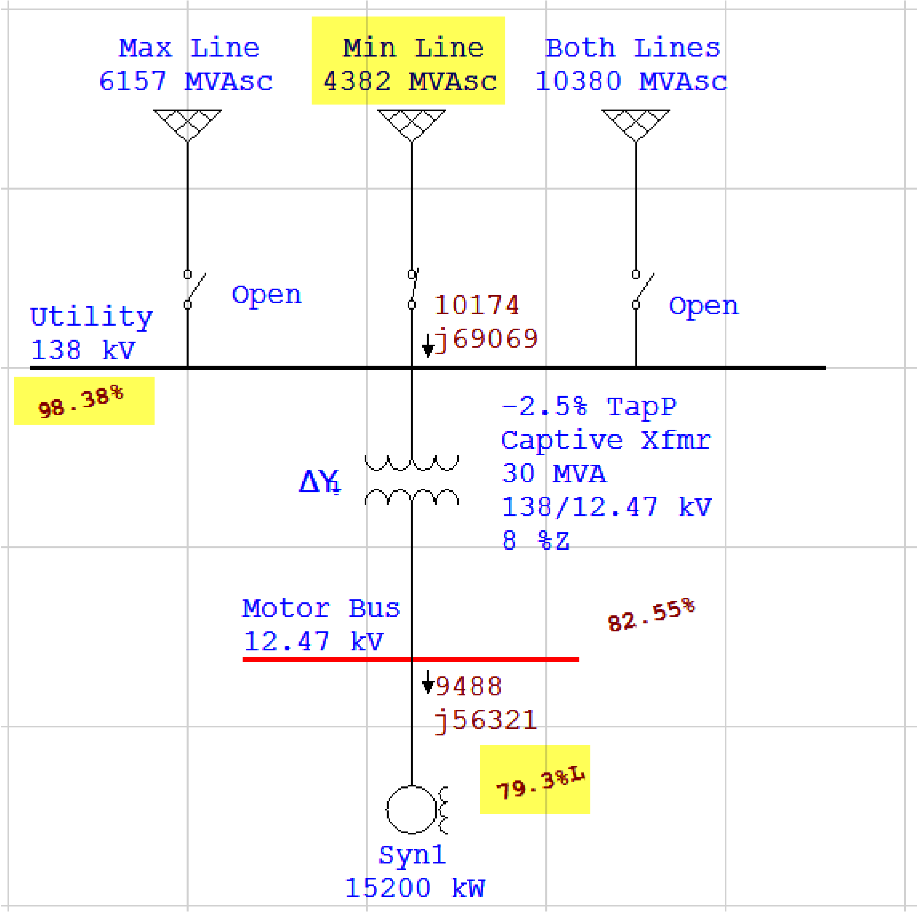
Starting motor on a captive transformer - example



- Reducing transformer impedance is similar to increasing the size, but should be less of a cost adder.
- With an 8% impedance the motor terminal voltage increases to just over 80%.
- The drop in the utility reduces slightly to 0.69% since the motor voltage increased thus the inrush current increased.

Motor Starting Studies – Captive Example

Starting motor on a captive transformer - example

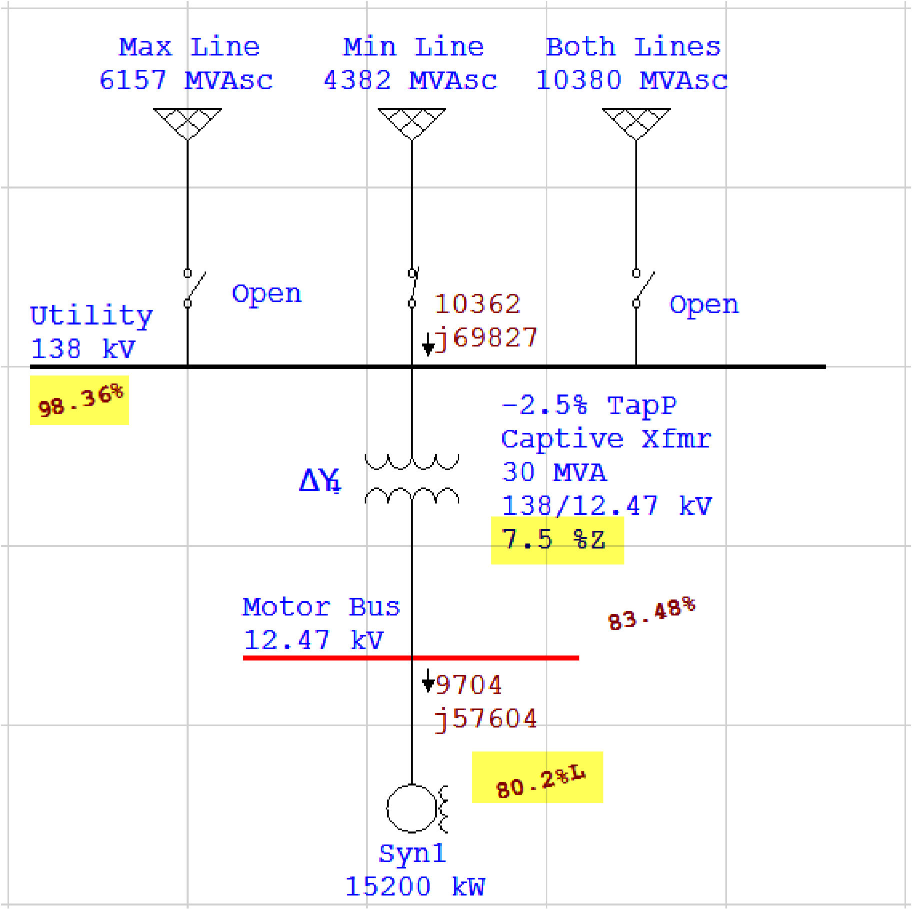


- Now consider starting with one of the two utility lines out of service. Using the weakest line is worst case.
- The voltage drop in the utility is 1.62% which is less than the 2.0% limit,
- But the motor terminal voltage drops to 79.3% which is unacceptable.

→ Try lowering the transformer impedance a little more.

Motor Starting Studies – Captive Example

Starting motor on a captive transformer - example



- With a 7.5% impedance the motor voltage increases to just over 80% and is now acceptable.
- The drop in the utility increases slightly to 1.64% but is still acceptable.

→ This example identifies a workable solution, but requires that the transformer and motor be specified as defined.

→ Since there is margin in the utility drop results, a slightly larger transformer could be considered.

Motor Starting Studies – EDG Example

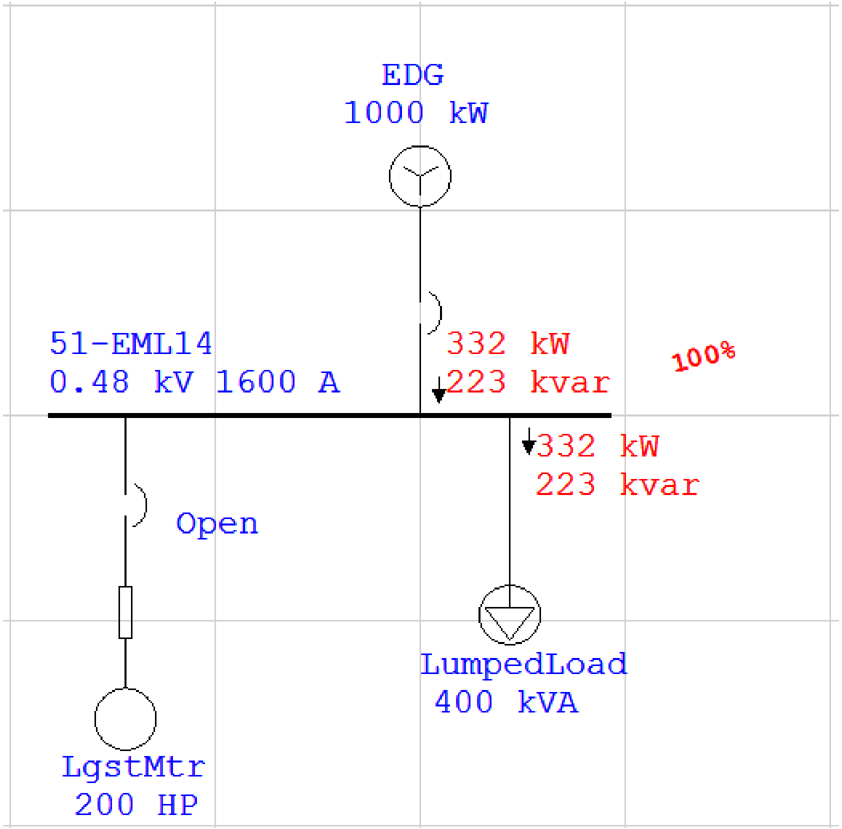
Starting motor on Essential Diesel Generator (EDG)

- Traditional industry practice assumes the generator automatic voltage regulator (AVR) responds in the transient time frame thus the voltage drop through the EDG internal impedance is defined by the transient reactance.
- Generator reactances for EDGs can vary widely. Best practice is to define the motor starting requirements in the EDG specification and use quoted data in preliminary studies.
- When necessary, use typical data from previously installed units.
- The generator bus voltage is set by the automatic voltage regulator and can assumed to be nominally 100%.

Motor Starting Studies – EDG Example

Engineering & Construction

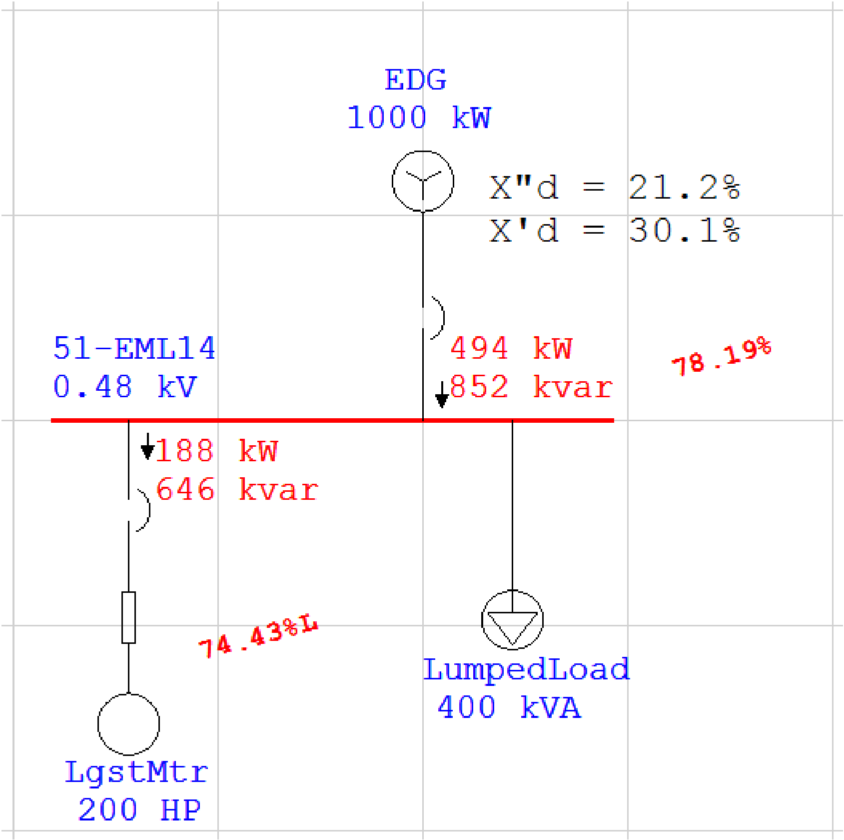
Starting motor on Essential Diesel Generator (EDG)



- Regardless of operating load, the generator bus voltage should be maintained at 100% nominal pre-start.
- Be sure that your study software models the voltage drop in the source/swing bus during the starting event.
- (check what SKM does)

Motor Starting Studies – EDG Example

Starting motor on EDG – using prior data



- These reactances are unusually high, but are real.
- Note that the X’d is around 150% of the X”d value.
- To maintain 80% on the motor terminals a much lower X’d reactance is needed.

Motor Starting Studies – EDG Example

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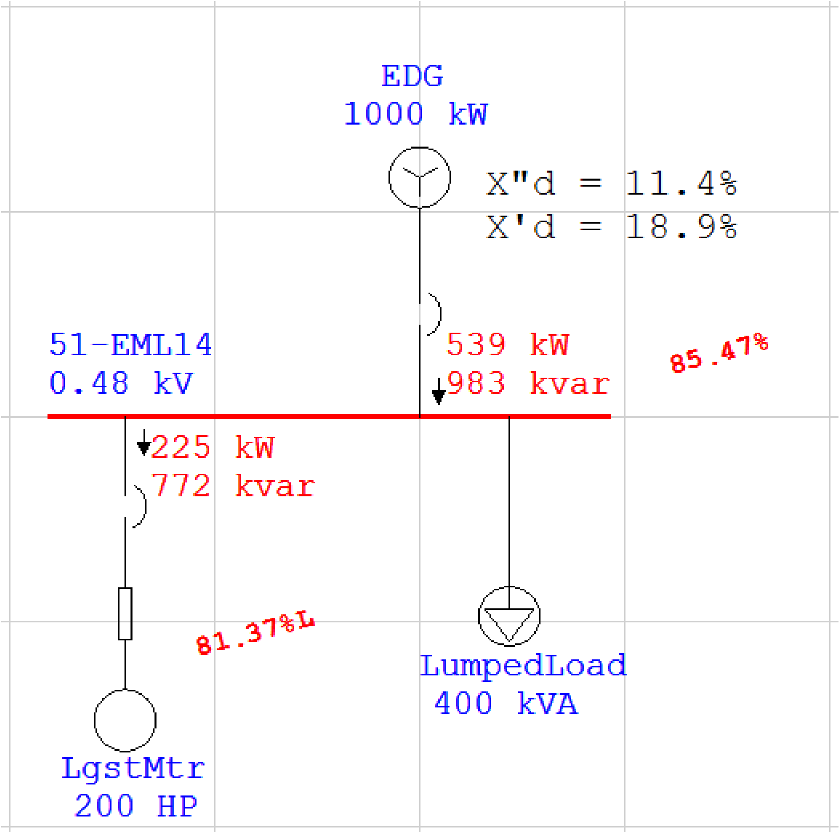
Starting motor on EDG – using other prior data

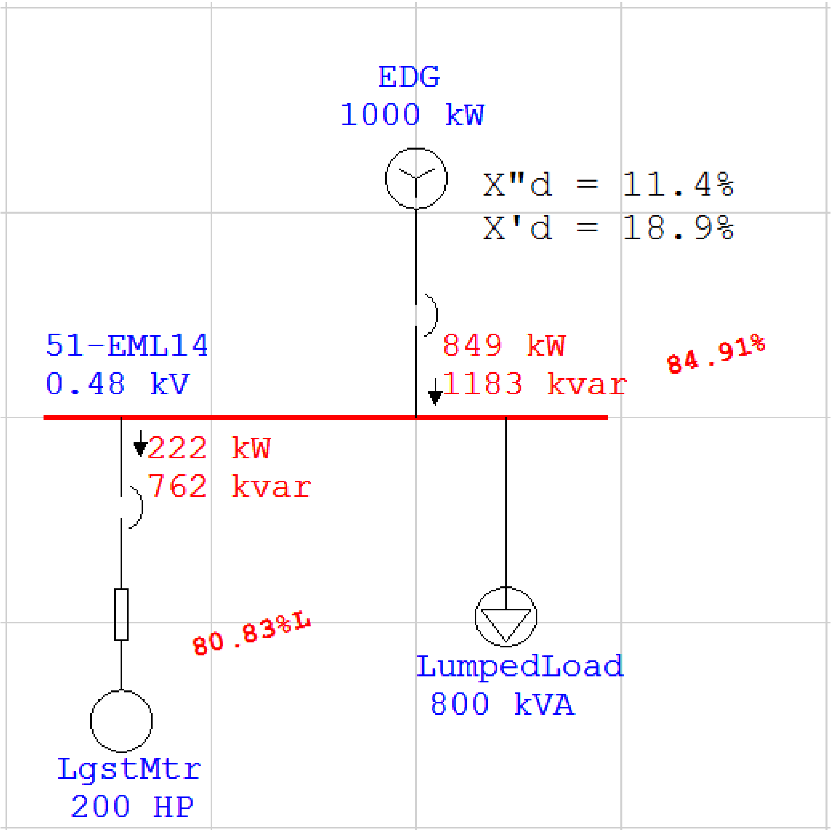


- These reactances are also real and more typical.
- Again, the X’d is around 150% of the X”d value.
- In this case the bus and motor terminal voltages are both in acceptable ranges.
- Assuming that the SC calcs are acceptable with the X”d of 11.4%, the EDG supplier must be advised to target these values.

Motor Starting Studies – EDG Example

Engineering & Construction

Starting motor on EDG – affect of more pre-start load



- On the previous slide the load pre-start load was 400 kVA and the bus and motor terminal voltages were 85.5% and 81.4%, respectively.
- Despite twice the load, the bus pre-start voltage will still be 100% due to the AVR.
- The approximately 0.6% lower voltages occur due to constant kVA loads drawing more current at the lower voltage.

Questions