CURRENT LIMITING FUSES EVALUATION ON LOW VOLTAGE SECONDARY SELECTIVE SYSTEMS WITH CLOSED TIE BREAKERS

Rakan El-Mahayni
Senior Member, IEEE
Saudi Aramco
P.O. Box 11039
Dhahran, 31311
rakan.mahayni@aramco.com

Shabir Khan, PE
Senior Electrical Engineer
Saudi Aramco
P.O. Box 7490
Udhailiyah, 36527
shabir.khan.1@aramco.com

Rashid Al Rashidi
Member, IEEE
Saudi Aramco
P. O. Box 18162
Dhahran, 31311
rashid.rashidi@aramco.com

AbduAllah Alnujaimi
IEEE Member
Saudi Aramco
P.O. Box 18162
Dhahran, 31311
abdullah.alnujaimi@aramco.com

Abstract: Current Limiting Fuses (CLFs) have been utilized in low voltage systems to limit short circuit currents to meet short circuit duty requirements. For the facility under consideration, CLFs have been used as an integral part of power circuit breakers within secondary selective switchgears operating with normally closed tie breakers. CLFs was selected to limit the short circuit current contribution to downstream equipment such as motor control centers. The application was based on the fact that current limiting fuses would reduce the let-through fault current to an appropriate value provided that the fault current is within the current limiting range of the CLF. Without this limiting effect, the MCCs would have been underrated from a short circuit duty standpoint. Research paper published in the early nineties proved the CLF's current limiting effect can be impaired when circuit breakers located within the downstream MCC buckets are of repulsive contact type. Currently the application of CLFs requires careful evaluation as stipulated by the National Electric Code (NEC). The facility under consideration was surveyed based on NEC requirements and violations were discovered. Alternative solutions are discussed to meet short circuit duty requirements. [1].

Index Terms — Current Limiting Fuses, Short circuit duty, Current Limiting Reactors.

I. BACKGROUND

The facility under consideration is connected to a 230 kV grid through a Gas Insulated Substation (GIS) with a double bus single breaker configuration. The GIS receives power through two 230 kV interconnections from utility and cogeneration plants.

Power is delivered to primary distribution switchgears from the GIS via two 230/13.2 kV three-windings step down transformers. The 13.2 kV switchgears are operating with normally open (N.O.) bus-tie breakers with auto bus transfer scheme. The low voltage switchgears located at downstream unit substations are designed to operate with normally closed (N.C.) bus-tie breakers with no provision for auto bus transfer. Figure 1 demonstrate a simplified power distribution network at different voltage levels including 13.2 kV and 0.48 kV.

Each process area has its own dedicated unit substation that receives power from the main primary distribution substation via 13.2/0.48kV transformers. The unit substations shown in figure 1 has two three windings transformers feeding two double ended switchgears providing power to 480V process loads via Motor Control Centers (MCCs). The feeder breakers feeding the MCCs have integral current limiting fuses, and the downstream 0.48 kV MCCs short circuit rating was selected based on the current limiting characteristics of CLFs.

The facility under consideration with the single line shown in figure 1, received a recommendation from a design office to consider existing CLFs in evaluating the short circuit interrupting and withstand capability of all existing motor control centers (MCCs). In addition, the design office recommended the consideration of CLFs to reduce arc flash incident energy at the aforementioned MCCs. This protection philosophy was prevalent at the 1980s where it was believed that CLFs would unconditionally limit the fault current regardless of what protection device exists downstream. A simplified power system model is shown in figure 2 with the three-phase fault current contributions in the low voltage system under consideration. Furthermore, figure 3 illustrates the short circuit contributions with the MCC bus being faulted. Approximately, 62kA is being contributed from the LV switchgear bus down to the MCC bus through the fused power circuit breaker.

Generally speaking, when the fault current is greater than the current limiting threshold of the CLF, CLF limits the RMS and peak values as well as the duration (to less than ½ cycle) of the fault current, figure 4. The let-through fault current can be determined based on an analytical method known as the "up-across and down" method. CLFs are typically provided with let-through charts such as the one shown in figure 5 [2]. However, this method has its limitations as will be explained later

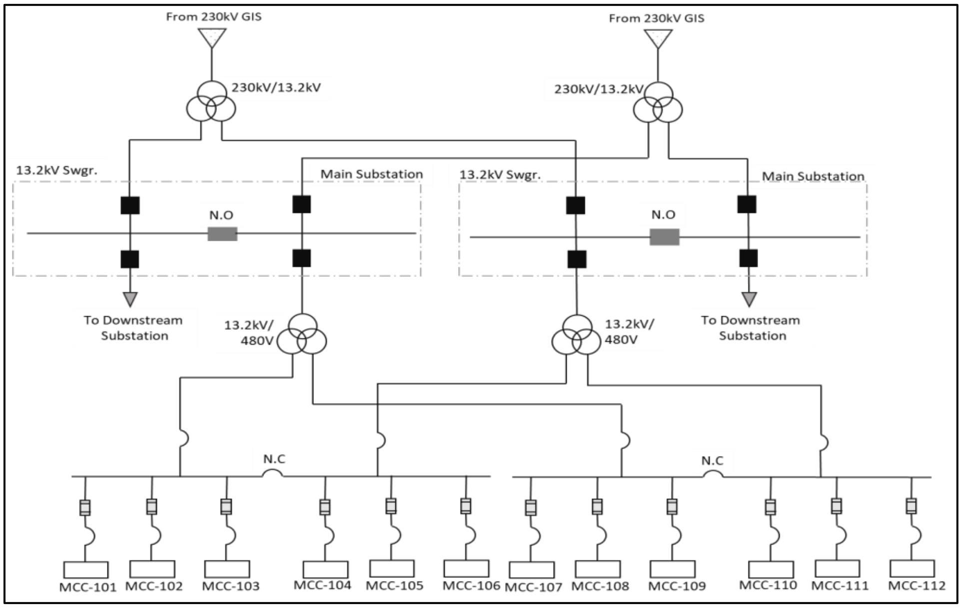

Figure 1: Overall Single Line Diagram

II. ANALYSIS OF CURRENT LIMITING FUSES PERFORMANCE

The following is a step-by-step analysis for the application of CLFs:

1) Current-Limiting Fuse (CLF): A fuse that limits the peak and the duration (to less than ½ cycle) of the prospective fault current. CLF acts in a current limiting manner when the prospective fault exceeds its current limiting threshold. IEEE Buff book states: “Only Class G, Class J, Class L, Class R, Class CC, and Class T may be marked current limiting”. Figure 4 demonstrate the behavior of a current limiting fuse and its effect in limiting the peak and duration [2].
2) Fuse manufacturers provide let-through charts to determine peak and RMS let-through currents based on the magnitude of the prospective fault current. This can be achieved using the “up-across and down” method as shown in Figure 5. For example, when the prospective fault current in this case is 30 kA. A Class-L 800 A rated fuse would limit the peak let-through current to 38 kA and the rms current to15 kA. It is worth mentioning, had the prospective fault current been less than the current limiting threshold (approx.12 kA, marked by red x on the chart), the fuse would not act in a current limiting manner (i.e. will be like a normal fuse).
3) CLFs can be installed with low voltage power circuit breakers to increase their short circuit interrupting capacities. Figure 6 shows a fused power circuit breaker with a current limiting fuse. The fused breaker’s short circuit rating is 200 kA.
4) A typical application is shown in Figure 4 where the prospective short circuit current at MCC-101 is 62 kA while its short circuit rating is 25 kA.
5) Considering 600 A rated fuse, using the let-through chart in Figure 5, the rms let-through current at MCC-101 is 15 kA (considering 62 kA prospective fault current as shown in green lines on figure 5). Theoretically, this would make the MCC rated properly since its short circuit rating is 25 kA (greater than 15 kA). Unfortunately, this is not always true as it will be explained in the following steps.

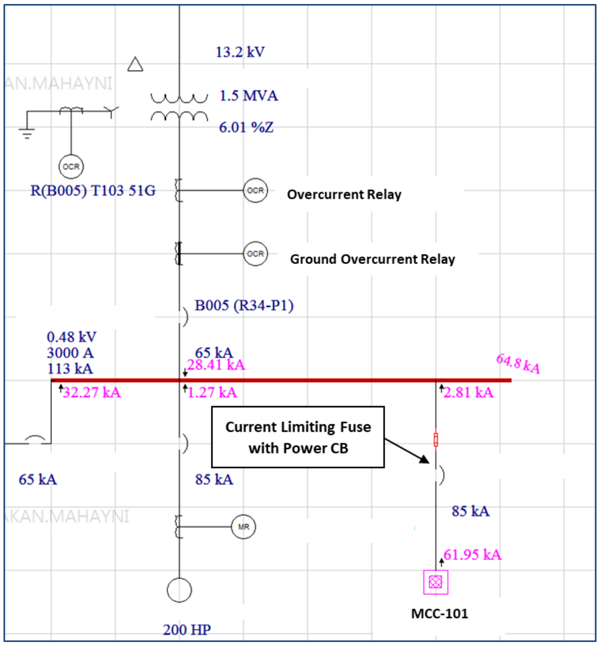

Figure 2: Simplified LV Power System Model

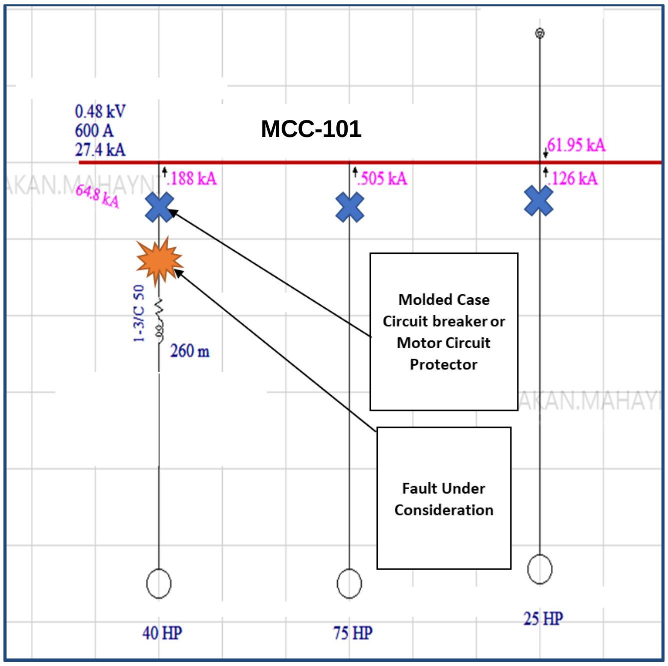

Figure 3: Short circuit results for a specific MCC protected by an upstream CLF

6) In order to utilize the fuse's let through charts using the "up-across and down" method to determine the downstream let-through short circuit current, the contact of the downstream MCC's molded case circuit breaker (MCCB) must be of a non-repulsive type [2][3].
7) The original MCCBs models available in the facility were all of non-repulsive type. However, over the years many changes happened in the MCCs where new MCCBs with repulsive type contacts were installed. It is worth mentioning that all modern MCCBs and MCPs utilize the repulsive contact technology.

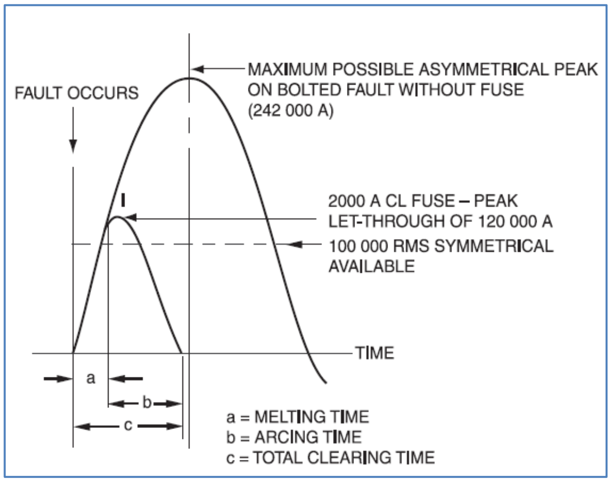

Figure 4: Typical current limitation showing peak let-through current and total clearing time [2]

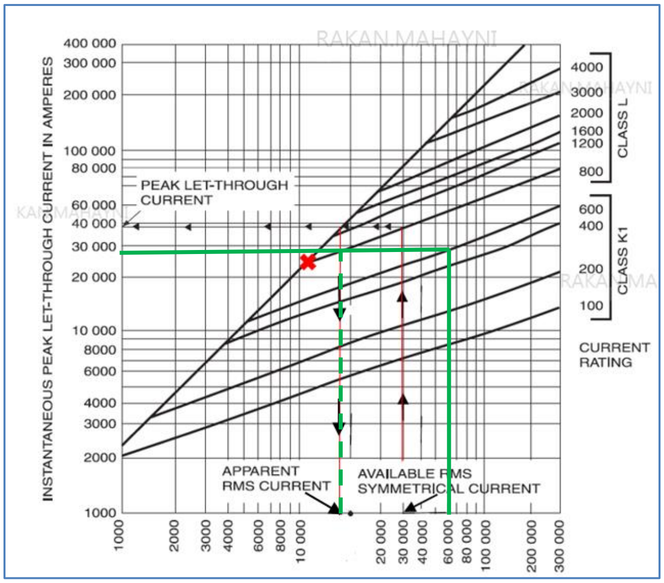

Figure 5: Typical let-through RMS and peak current as a function of prospective fault current [2]

Figure 6: Sample fused power circuit breaker with a current limiting fuse

8) MCCBs with repulsive or "blow-apart" contacts might impair the current limiting effect of the upstream current limiting fuses. This is because they demonstrate a dynamic arc impedance during interruption, thus, reduce the fault current seen by the fuse. As a result, the fuse is very likely to act NOT in a current limiting manner. [3]
9) In order for the fuses to be considered in the MCC short circuit duty evaluation, they must be series rated/tested with downstream MCCBs. This can only be achieved by testing. Typically, MCCB and fuse manufacturers publish such testing data where they list all tested combinations of fuses and breakers. This is mainly common in panelboard applications (i.e. not for motor circuits).
10) Utilizing series rated/tested fuses and MCCBs is restricted by the NEC (Article 240.86(C)). NEC (Article 240.86(C)) states that in series rated combinations, the

total motor full load amps (FLA) shall not exceed one percent (1%) of the downstream MCCB's short circuit rating. As an example, for MCC-101, the total motor full load amps is 690 A which is much greater than 250 A (1% of 250 kA- MCC SC rating). Therefore, achieving series rating is very difficult in a motor control center application since the majority of loads are motors.

11) For MCCs that have all breakers with non-repulsive type contact, based on NEMA [4], the following restrictions applies to the fuse application:

a. The fuse shall reduce the let-through current to a value below the interrupting rating of the downstream circuit breaker.
b. The fuse shall clear the circuit at a time before the contacts of the downstream circuit breaker begin to open (true for breakers with non-repulsion type contacts)
c. Items (a) and (b) are true for all current levels from the rating of the downstream circuit breaker through the series rating of the combination (not just at the maximum current level of the system).
d. It has an interrupting rating at or above the engineered series rating.

III. APPLICATION OF CURRENT LIMITING REACTORS

Installing current limiting reactors (CLRs) would reduce the prospective short circuit current to acceptable levels. However, the following shall be considered:

1) CLR shall not cause more than 3% voltage drop.
2) CLR's enclosure shall be made of non-ferrous material (i.e. aluminum) to prevent circulating currents. Figure demonstrates typical CLRs layout drawings.
3) CLR enclosure dimension shall match the existing MCC's vertical dimensions (depth and height) as shown in figure 7.
4) CLR shall be sized as follows:

With the prospective fault current is 65 kA out of which, 61.95 kA is contribution from upstream as shown in figure 3.

Since the MCC's short circuit rating is 25kA, the goal is to design a CLR to limit the fault current to 20 kA. Using the MVA method for short circuit calculations [5]:

Target I_{sc} for MCC-101 is 20 kA. Therefore, Target MVA_{SC} at MCC-101 is: $20 * 0.48 * \sqrt{3} = 16.627\ MVA$

Prospective I_{sc} at MCC-2B is 61.95 kA (without motor contribution). Therefore, Prospective MVA_{SC} at MCC-101 is:
$61.95 * 0.48 * \sqrt{3} = 51.5\ MVA$
Solving for the $MVA_{CLR-Let\ Through} = C$

$$\frac{C*51.5}{C+51.5} = 16.627;\ C = 24.55\ MVA$$

$$Z_{reactor} = \frac{0.48^2}{24.55} = 9.385 * \ 10^{-3}\ Ohm$$

$$L_{reactor} = \frac{9.385 * 10^{-3}}{2\pi*60} = 2.49 * \ 10^{-5}\ henrey = 24.9\ \mu H$$

A reactor with $0.01\ Ohm$ will be selected (i.e. standard size). This reactor will cause additional voltage of 1% under maximum load operation. The reactor let-through current will be 19.46 kA.

Now, we will rerun the short circuit duty calculations to verify the reactor selection.

$$I_{sc-new-MCC-101} = 21.78\ kA,\ \frac{X}{R} = 11.3;$$

The software calculated X/R exceeds the MCP/MCCB's test X/R; therefore, the calculated short circuit current will be adjusted by software to become $I_{sc\ adjusted} = 25.62\ kA$ which exceeds the short circuit rating of the breaker (25kA). Hence, the next standard reactor size will be selected which is $0.015\ Ohm$. This selection will result in the following outcomes:

$$L_{reactor} = \ 40\ \mu H,$$

$$I_{sc-new-MCC101} = 16.8\ kA, \qquad \frac{X}{R} = 12.3$$

$$I_{sc\ adjusted} = 20\ kA\ which\ is\ less\ than\ 25\ kA\ (MCP\ SC\ rating)$$

$$VD\%_{MCC-101} = \ 97.5\ \%$$

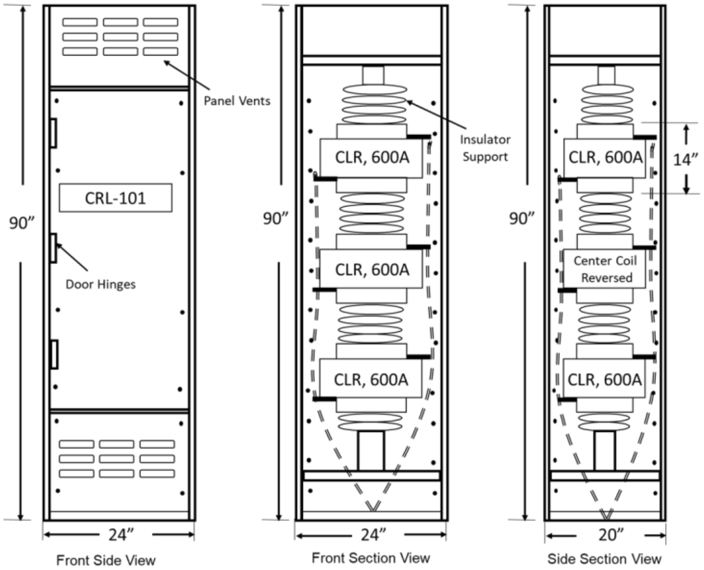

Figure 7: CLR layout drawings- MCC section

IV. METHODOLOGY TO EVALUATE AN INDUSTRIAL FACILITY

A seven-step methodology was developed to verify the CLF application based on the aforementioned NEC requirements. The criterion considers equipment information such as rated short circuit (SC), type of MCCBs; repulsive or non-repulsive, percentage of motors' load, motors' short circuit contribution and available short circuit current.

1) Step 1: Check the available adjusted symmetrical short circuit without considering CLF

effect. If this value is already less than the MCC rating, no need for further evaluation. If this value is higher than the short circuit rating, proceed to step 2.

2) Step 2: Check MCCBs' types and confirm that all MCCBs are of non-repulsive type. If this is the case, proceed to step 3, otherwise CLF impact cannot be relied on and alternative solutions shall be considered to meet the MCC's short circuit duty requirements.
3) Step 3: Check the motor contribution to the MCC bus and confirm that it is less than 1% of the short circuit rating of the MCC. Relocate some loads if applicable. If this is the case go to step 4, otherwise CLF impact cannot be relied on and alternative solutions shall be considered to meet the MCC's short circuit duty requirements.
4) Step 4: Obtain the let-through current for both RMS and peak values using the up-across-down method using the fuse's curve along with the available maximum upstream short circuit current contribution.
5) Step 5: The obtained let through values should be added to the rms and peak motor short circuit contributions to find the available short circuit current at the MCC bus. Motor's rms SC contribution can be estimated at six time the full load amps (FLA), and motor's peak short circuit contributions can be found approximately by multiplying the rms value by a factor of 2.6.
6) Step 6: The available let-through peak and rms SC values should be less than the respective rms and peak interrupting ratings of the lowest rated MCCB within the MCC. The MCC's short circuit rating can be found on the nameplate, and the peak value can be derived by finding the MCC test X/R ratio, which is typically 4.9 for MCCs based on 0.2 test power factor [7]. This yields a peak multiplication factor of 2.2 as shown in figure 8. If this condition is met, proceed to step 7. If not, then even with the upstream CLF, the downstream MCC is considered as over-duties.

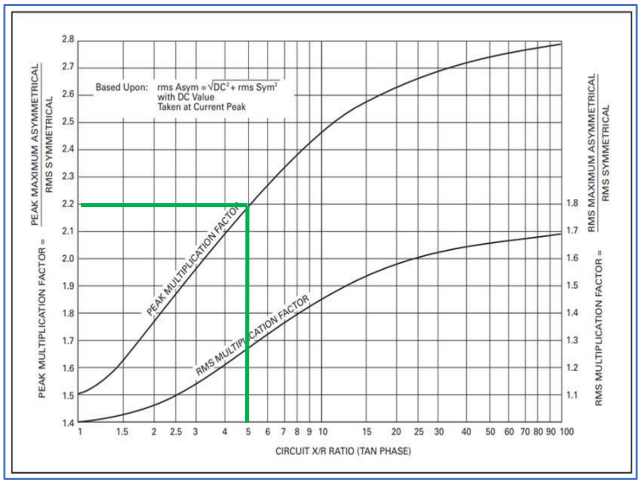

Figure 8: Circuit X/R Ratio [6]

7) The downstream devices' short circuit rating shall be higher than the threshold current liming value. This is to ensure that the fuse will act in a current limiting fashion for all SC values higher than the MCCB rating.

If the MCC passed all the above tests, then no action is needed and replacement of the non-repulsive type MCCBs shall be restricted to in-kind replacement and labels can be installed on MCCs to indicate restriction requirements.

Refer to below example where the required calculations are shown as per seven step criteria explained previously. The available short circuit values are based on a short circuit study and CLF data is considered from manufacturer datasheet. below provides step by step calculation example:

TABLE I
STEP BY STEP SOLVED EXAMPLE

Step #	Criterion Details	Values	Outcome
Step 1	Available Short Circuit Current without CLF effect	62 kA	Fail
	Smallest MCCBs SC Rating (MCC-101)	25 kA	
Step 2	Check MCCBs' Types	Model: All breakers are Non-repulsive type	"Pass"
Step 3	Motors connected load shall be less than 1% of lowest MCCBs SC rating	= (478/25000)*100 = 1.91%	Fail. Motors' load exceeds 1%.
Step 4	CLF let-through RMS + Motor RMS Contribution (kA)	17.5 kA	Pass
	Rated RMS SC Current (kA)	25 kA	
Step 5	CLF let-through Peak RMS + Motor Peak RMS Contribution (kA)	45.5 kA	Pass
	Rated RMS Peak SC Current (kA)	54.5kA	
Step 6	Current Limiting Threshold of Fuse (from CLF Datasheet)	11kA	Pass
	Interrupting RMS SC Rating	25kA	

Step 7	Decide upon the required action based on the outcome of Steps 1 ~ 6 - If the outcome of Step 1 is “Pass” No action is needed. Do not proceed to further steps. - If the outcome of Step 1 is “Fail”, Continue with steps 2 ~ 6. If all of steps 2~6 “Pass”, no action is needed. Install label on MCCs to restrict replacement of non-repulsive MCCBs. OR If any of steps 2~6 “Fails”, alternative solutions need to be evaluated including opening the tie-breakers, installing current limiting reactors or replacement of MCC.

The seven-step criterion was applied to all existing 480V MCCs at the operating facility. Below is the summary of the outcome:

- 27% of the total MCCs “Passed” the criteria. However, majority of MCCs at each substation “Failed” to meet the criterial and are still considered to be over-duties.
- 13% of the total MCCs across different substations “Failed” the criteria due to presence of one or more repulsive type MCCBs. All newly manufactured MCCBs are repulsive type so it is not possible to upgrade the repulsive type MCCBs with non-repulsive type.
- Installation of CLR was evaluated but not considered for implementation. The MCCs at the substations are installed back-to-back and on some instances side-by-side. Sufficient spacing was not available to install CLR beside each MCC. Moreover, it was advised that 9” magnetic clearance is recommended by CLR manufacturer between MCC and reactors’ enclosures to prevent magnetic interference. Such clearance was not available.

After conducting a comprehensive risk assessment, it was decided to open tie breakers at substations where losing one incomer will not result in process shutdown. This approach resulted in resolving the short circuit over-duty issues for 68% of the total MCCs. For other substations where opening the tie-breakers would result in process shutdown, it was considered the replacement of the remaining 32% of the total MCCs with fully rated ones. This has been successfully completed and leads to maintain and sustain the facility’s safety and operation.

V. RECOMMENDATIONS

With the presence of downstream modern breakers with repulsive contact type, CLF utilization is not acceptable to meet short circuit duty requirements at downstream MCC’s. A possible solution is to upgrade the short circuit rating of an existing MCC. This is not an easy task since it involves changing all buckets with new properly rated components as well as re-bracing the bus. This will require a major down-time and it is cost prohibitive. However, the short circuit over duty condition can be resolved by, one of the following:

1) Open the tie breaker at the switchgear level to reduce the prospective short circuit current and arc flash incident energy. Initial assessment revealed that opening the tie-breaker was not feasible because of the following reasons

   a. Loss of a 13.2kV/480V transformer will cause process unit shutdown due to power interruption to several 480V MCCs. Under some scenarios, this would lead to total shutdown of the facility.
   b. The three windings transformer design makes it more complicated as loss of a transformer would interrupt two 480V buses causing shutdown of large number of process loads.
   c. The 480V switchgears do not have auto bus transfer scheme as the tie-breakers were designed to be N.C. With normally open tie breakers, operators will have to manually close the tie in case of loss of an incomer and start the restoration of loads.
   d. It is challenging to implement auto bus transfer scheme for existing switchgears which have electromechanical relays and have arc flash incident energies above 40cal/cm2.

2) Install current limiting reactors to reduce the prospective short circuit currents to be below the MCC SC rating. See section IV for details on reactor sizing and selection for a sample MCC.

3) Prioritize the replacement of the under-rated MCCs and consider the system short circuit current without the current limiting fuse effect in the purchase order of the new MCCs.

VI. CONCLUSION

Careful analysis must be conducted to evaluate the performance of current limiting fuses especially when breakers with repulsive contacts are present downstream. Current limiting reactors can be considered as a viable option provided there is a sufficient space. Upgrading equipment to meet the short circuit duty requirements can be adopted as a last resort.

VII. REFERENCES

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VIII. VITAE

Rakan El-Mahayni, PE (IEEE S ’04, M ’07, SM ’09) is currently the Electrical Systems Design and Automation Standards Committee Chairman for Aramco based in Dhahran, Saudi Arabia. In 1998, he graduated from University of Damascus, Syria, while he was working for Siemens AG as a high voltage testing and commissioning engineer. After working for Powell Industries as a field service engineer in Philadelphia, PA in 2001, he joined Eaton Corporation with a similar role in the Bay Area, CA. In 2005 he transitioned to a power systems engineering role with increasing responsibilities. In 2012, he joined Aramco’s Consulting Services Department as a consultant. He is a licensed Professional Engineer in CA, and received a MSEE from California State University, Sacramento, in 2006.

Shabir Khan, PE is currently working as Senior Electrical Engineering for Saudi Aramco. In 2007, he graduated from Mehran University of Engineering & Technology, Pakistan. He started his professional career in Pakistan by working as Electrical Engineer at Pakarab Fertilizers Company & as Design Engineer for JGC-DESCON Engineering, Pakistan. In 2010, he joined Al Mashariq Company, Saudi Arabia as Power Systems Engineer. In 2015, he joined Saudi Aramco as Electrical Engineer. In 2024, He completed his Masters of Engineering degree in Sustainable & Renewable Energy from King Fahd University of Petroleum & Minerals, Saudi Arabia.

Rashid Al-Rashidi received his B.S. in Electrical Engineering from King Fahd University in Dhahran, Saudi Arabia in 2008 and MS degree from Michigan Technological University in USA in 2014. In 2008, he Joined the Saudi Aramco’s Consulting Services Department as an Electrical Engineer. Mr. Rashidi is a licensed professional engineer in Saudi Arabia since 2012 and he specializes in power system analysis and design.

Abdullah Al-Nujaimi (M’12) received Bachelor’s (First Hons.) and Master’s degrees in electrical engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, in 2013 and 2018 respectively. In July 2013, he joined Saudi Aramco working for the Consulting Services Department as a Power System Analysis and Design Engineer. He also worked with Ras Tanura Refinery as a Technical Support Engineer for two years. His primary interests are power systems studies, power system quality, and electrical equipment troubleshooting and commissioning.