HOW A TRACTION POWER FEASIBILITY STUDY ENSURES THAT A RAILWAY ELECTRICIFICATION SYSTEM WILL FUNCTION AS INTENDED FOR ALL PLAUSIBLE OPERATING CONDITIONS

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Abstract–**Railways are relied upon as a means for transporting passengers and goods across short, medium, and long distances. In modern railway systems, electricity is a convenient source to power an efficient mass transportation system. An important part of this electrical system are the traction power substations whose function is to convert the incoming commercial electrical supply to a form usable by the motive power on the train. The electrical energy from the traction power substation is then delivered to the train via an overhead catenary line or an energized third rail. This paper discusses how a traction power feasibility study will ensure that a railway electrification system will work as intended during all plausible operating conditions. The topics presented include the general overview of traction power systems, the complexities associated with re-designing or modernizing a traction power system, and how a feasibility study might avoid some of the common pitfalls.**

I. INTRODUCTION

Railway electrification systems are typically classified into three main categories: light rail, rapid transit, and commuter rail. Light rail systems are most frequently used in transit applications such as trams, streetcars, passenger movers, and monorail systems. Rapid transit systems consist of metro and subways which are higher capacity systems. Commuter rail systems consist of intercity passenger or freight/cargo transport systems that travel at higher speeds and cover longer distances.

Railway systems operate on either AC power or DC power based on the type of application. A light rail system is most often supplied by an AC or DC overhead catenary line, while rapid transit systems are often supplied via a DC energized third rail; and commuter rail systems operate via an AC overhead catenary line. An effective design of a traction power delivery system will ensure that a transit system will operate reliably and efficiently.

II. DC TRACTION POWER SYSTEMS

Most DC traction power systems operate at voltages that range between 500V DC and 1500V DC. Modern design practice often involves the ANSI Circuit #31 philosophy. The components of a DC traction power system consist of the following components (see Figure 1):

- AC Utility Switchgear. This is the service entrance switchgear that receives power from the utility company. This equipment is used to distribute power to the rectifier transformers and auxiliary station-service transformers.
- Rectifier Transformer. This frequently consists of a 2-winding or 3-winding, extra heavy-duty transformer, that steps down the AC utility voltage to the railway system's equivalent operating voltage. This equipment also sets the commutating reactance necessary for safe operation of the downstream rectifier.
- Rectifier. This equipment converts the AC voltage received from the rectifier transformer to the DC voltage to meet the railway system's desired requirement. Modern systems consist of combinations of either 6-pulse rectifiers in parallel or 12-pulse rectifiers with dual AC inputs and an interphase transformer.
- DC Traction Switchgear. This switchgear distributes power received from the rectifier output to the railway system via an overhead catenary line or an energized third rail.
- Auxiliary Station Service. This equipment consists of the low voltage electrical distribution system, fed by an auxiliary transformer, which is used to supply power to the ancillary loads such as annunciators, lighting, receptacles, battery systems, SCADA devices, HVAC, etc.

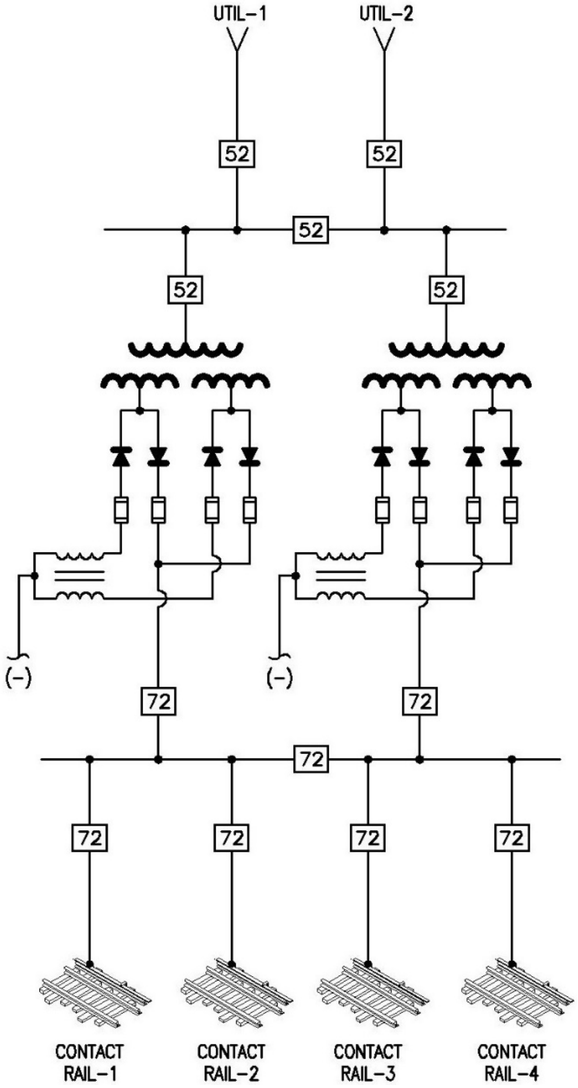

Figure 1: Typical DC Traction Power System Layout (Additional breakers, switches, relays, and protective devices not shown for simplicity)

III. AC Traction Power Systems

Most AC traction power systems operate at voltages that range between 11kV AC and 25kV AC. The AC system can operate at either 50/60 Hz or at a reduced frequency of 16/25 Hz to minimize the effect of reactive power losses. The components of an AC traction power system consist of the following components (see Figure 2):

- AC Utility Equipment. This is the service entrance equipment that receives power from the utility company. This equipment is used to distribute power to the step-down transformers and auxiliary station-service transformers.
- Step-Down Transformer. This transformer steps down the AC utility voltage from its nominal supply to the railway system's desired voltage.
- Frequency Converter. A frequency converter is utilized when the traction power system operates at a lower frequency than the commercial supply frequency. This conversion equipment might consist of either a rotary converter (large motor-generator set) or a static converter (power rectifier-inverter device or a cyclo-converter).
- AC Traction Switchgear. This switchgear distributes the power received from the frequency converter to the railway system via an overhead catenary line (or other means of delivering power to the motive equipment). If the railway system frequency is the same as the utility system, auto-transformers may be employed in conjunction with these devices.
- Auxiliary Station Service. Similar to a DC traction power system, this equipment consists of the low voltage electrical distribution system, fed by an auxiliary transformer, which is used to supply power to the ancillary loads such as the battery systems, SCADA devices, annunciators, lighting, receptacles, HVAC, etc.

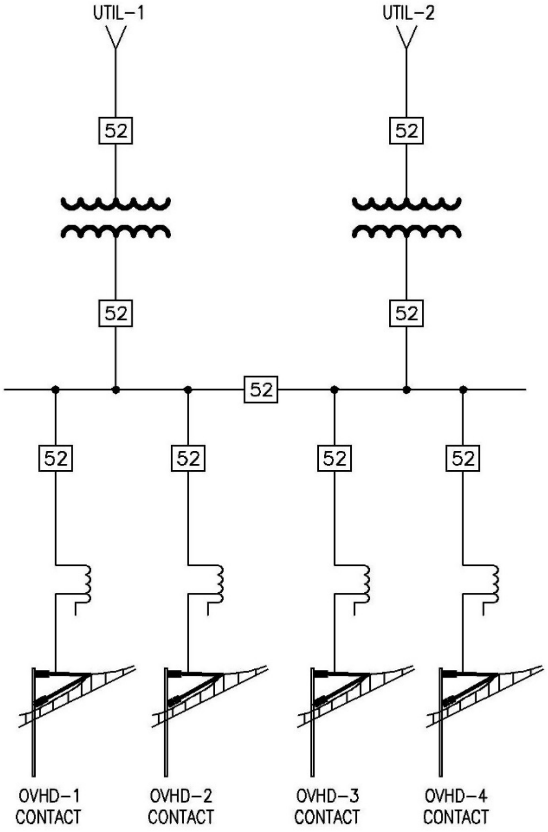

Figure 2: Typical AC Traction Power System Layout (Additional breakers, switches, relays, and protective devices not shown for simplicity)

IV. IMPLEMENTING A TRACTION POWER SYSTEM

Any electrified rail system, whether an AC traction power system or a DC traction power system, tends to be complex. What the casual observer or passenger sees from the outside only represents the "tip of the iceberg". Although there is a significant investment in the rolling stock, an even larger portion of the system is hidden from view. Modifying or modernizing such a system often presents huge engineering, application, and project management challenges for a railroad authority.

Any rail system must be able to permit multiple operating scenarios including simultaneous train starts, temporary system overloading, tie breaker operation, as well as the possibility for regenerative energy recovery. In addition to allowing operation during these conditions, the electrical protection system must be able to discern a fault condition and immediately initiate a system trip.

V. UPGRADING A TRACTION POWER SYSTEM

The complexity of a modern transit system cannot be overstated. From the moment passengers cross the threshold of what comprises the transit system infrastructure until the time they exit, public safety and security are priority number one. No single group of workers can manage it all at once. Dozens of systems and functions compete for attention in the arena where modern, comfortable, and above all a reliable mode of transportation is the goal. In this paper, the focus remains on the reliable operation of the traction power system.

Whenever a traction power system is upgraded, extended, or modified, its electrical characteristics are altered and its overall performance changes. With a well-crafted feasibility study, these changes can be visualized and analyzed well before a single piece of electrical equipment is specified or the construction activities commence [6]. The study scope can include, but not be limited to, such analyses as: (i) getting the expected performance for multiple operating scenarios; (ii) uncovering problem areas to avoid costly workarounds or retrofits; (iii) improving reliability issues; and (iv) avoiding unexpected impacts to current operation and maintenance procedures.

VI. FEASIBILITY STUDY CONSIDERATIONS

Structuring a feasibility study to include multiple operating scenarios allows the transit system engineers and management to understand what may happen during abnormal events such as:

- How would the system respond if there were a derailment at point "X" causing a third rail track fault?
- What would be the arc flash consequences for something dropped into the track pit at a passenger station?
- If multiple eight-car trains were to start almost simultaneously, how would a given power block perform during an unanticipated schedule change?

The above considerations are just a few of the many examples that would concern operations and maintenance personnel. While a single focus on electrical issues should not impact the performance and reliability of energy conversion equipment, motive power, rolling stock, or the track configuration; one cannot disregard the secondary effects.

VII. FEASIBILITY STUDY BENEFITS

When hypothetical events are applied to key areas of the system, unexpected problem areas within the system can be revealed [1] [2] [3] [5]. Such problems can then be corrected as part of the initial design thereby avoiding costly workarounds or field retrofits after the new equipment has been installed or commissioned. Such examples of benefits include the following:

<u>Impedance Bonds</u>. These devices are used to connect the insulated track segments to allow the continuity of the traction power supply while restricting the train sensing signals across the insulated segments (see Figure 3). When performing a system upgrade, a feasibility study can identify how a power system may respond differently due to a signaling system retrofit where the return impedance bonds have been changed or practically eliminated.

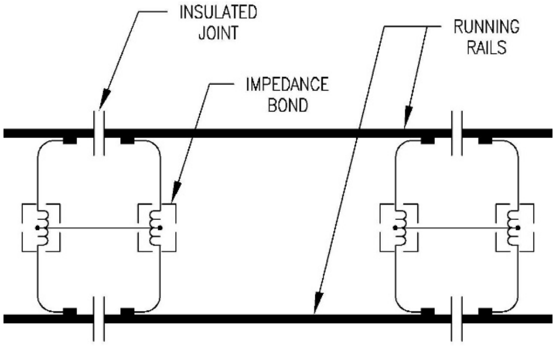

Figure 3: Impedance Bond Connection Arrangement

System Protection. A feasibility study can identify problems attributed to a ‘one size fits all’ philosophy in the protection scheme. Such a philosophy might not be ideal for an operating scenario that is based on multiple infeeds. Sometimes, protective devices may call for a trip on a particular infeed when such an action is not desirable for a given operating scenario. The analysis may indicate that a practical solution is to automatically switch the protection settings group to match the operating scenario (see Figure 4). This is something not previously possible with single-function electromechanical and solid-state relays.

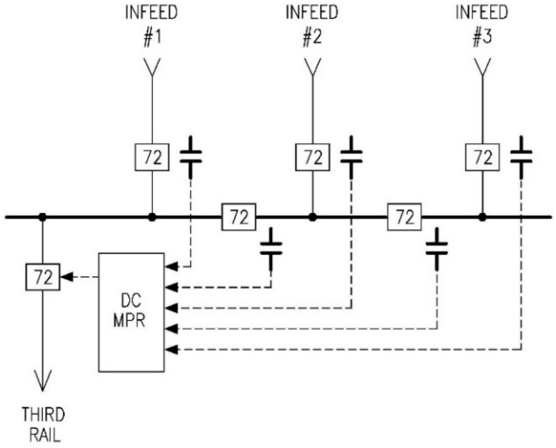

Figure 4: Adjustable System Protection Philosophy (Status of breakers can engage ‘group settings’)

Impact Load Analysis. Rectifier load sharing ensures proper operation of the traction power system prevents system overloads. The feasibility study can identify rectifiers, planned for system modernization, will not share load proportionally with existing units. This may occur where different rectifier ANSI circuit configurations are installed side-by-side, along with rectifier transformers of different designs or impedance parameters (see Figure 5). Such a scenario can often occur when a traction power system is transitioning from an old system to a new system while a transit system and the movement of trains must remain operational.

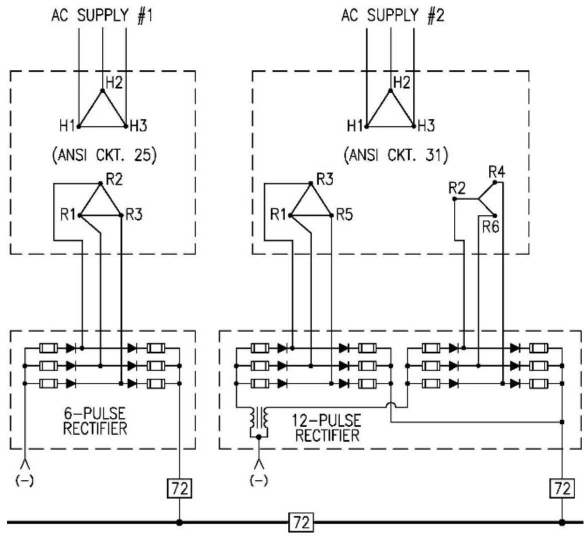

Figure 5: Unmatched Rectifier Configuration System (ANSI Circuit-25 and ANSI Circuit-31 in conjunction)

VIII. EQUIPMENT MODERNIZATION

New equipment designs, with different or enhanced features, may improve both the performance and reliability issues over the previous installed base. However, some items may prove to be high maintenance. This could be true in circumstances where an otherwise desirable feature becomes a maintenance problem because it frequently operates too close to its design limits.

Sometimes this is not a simple question of making something bigger or more ‘heavy duty’. A study may catch such problems. Traditionally, many systems have used either six or twelve pulse, single-quadrant operation rectifiers in their traction power substations. Suppose a transit authority has decided to evaluate the use of two quadrant, twelve pulse rectifiers at one of its modified substations. For such an analysis, a feasibility study could also include an inversion limit test analysis coupled with the short circuit study to determine overall performance under a variety of AC and DC system configurations. In such an analysis, the AC and DC systems become truly interactive and cannot be evaluated separately [6].

Station reliability as well as maintenance procedures could be severely impacted if such equipment were improperly specified because a feasibility study was not performed. Unless the equipment manufacturer has been supplied with detailed data surrounding the equipment to be furnished, their application analysis may not yield reliable data for successful long-term operation. This paper also examines features of specific analytical modules which may be used to address many of the system examples described herein.

IX. AVOIDING COMMON PITFALLS

An examination of hypothetical events, which could be imposed on a traction power system undergoing a redesign for rail service extension or simply for equipment modernization, is often a result of past operating experiences. Such experiences could include an instance where the system was unable to function as intended under a particular operating scenario. The desire on the part of railway operations and maintenance personnel is to not repeat a loss of service based on an unfortunate scenario.

This paper examines the main areas where analytical studies can be applied to avoid pitfalls in an otherwise sound design. Both the commercial AC supply and the DC conversion and distribution systems must be included in these analyses.

X. FEASIBILITY STUDY PROCEDURE

The first step would be to create a realistic electrical system model using an accurate set of one-line diagrams and record drawings. Different types of analyses should then be performed using this model. Such analyses should include the following:

- AC short circuit study
- DC short circuit study
- DC load flow study (w/ voltage performance)
- DC rectifier load sharing performance

Each of these analyses is usually undertaken as part of the project deliverables. However, typical project delivery methods leave gaps in the overall performance assessment. The supplier or manufacturer of the principal equipment may be asked to provide evidence of the anticipated performance via studies described in contract documents. Typically, this contract scope may not be sufficient to determine problem areas since such a scope may include only one station while ignoring the effect of adjacent ones.

Most transit authorities have a master electrical system model either created and maintained in house or by a contractor. A feasibility study performed using this model during the design phase of a project, will allow attention to be given to the interaction of the new work with the existing system, and avoid problems during the equipment acceptance process when the issues might be discovered too late to address adequately.

XI. COMPUTER MODEL SIMULATION

Typical commercial power system study software uses well-established and accepted algorithms to compute transient, steady-state, and interrupting short circuit currents for most power delivery devices. Although the graphic user interface of the commercial software may depict the AC and DC systems as one composite system, the study calculations are actually performed separately on the back end. The power system study engineer must, therefore, be aware of simulation model adjustments that must be made to achieve accurate performance.

While the DC short circuit study may focus on the magnitude of current for a third rail track fault and the resulting time constant associated with this fault, the range of these two parameters is extremely important when selecting protection settings. The corresponding time constant is sensitive to changes in the transit system’s automatic train controls and signaling systems modifications. If the transit authority is retrofitting its network with new train location detection, the older low frequency impedance bonds may be changed out for new high frequency devices. The feasibility study can examine the change between one block with old equipment and another block with new equipment.

If several rectifier substations are undergoing modernizations where older 6-pulse rectifiers are being replaced with new 12-pulse units and new transformers while these zones are being upgraded to high frequency signaling systems, it may be surprising to find that the additional IPT used in the proposed ANSI #31 rectifier configuration offsets the reduction in return circuit inductance due to the change in impedance bonds (see Figure 6).

Furthermore, suppose maximum harmonic reduction and smoothing has been specified. The solution may require a larger than normal IPT device and rectifier transformers with very high secondary coupling factors. When these factors are considered, the total

DC short circuit may increase due to the change in coupling factor on the new transformers while the DC fault current rate of rise may get reduced (see Figure 7).

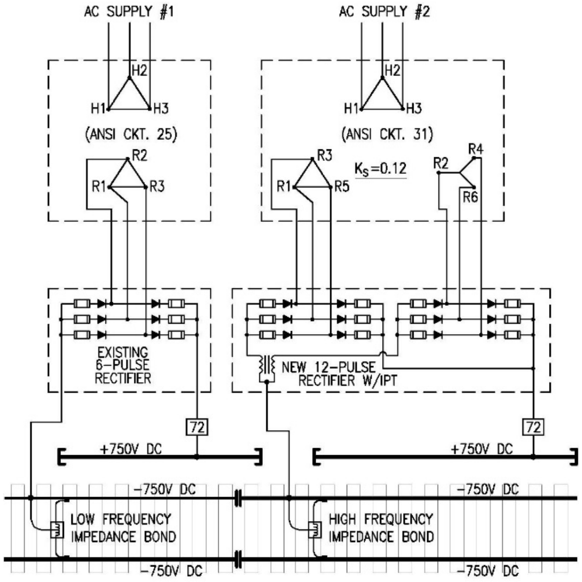

Figure 6: Traction Characteristics for a Typical System (Note that there is no significant difference between DC fault current and rate of rise between the two systems)

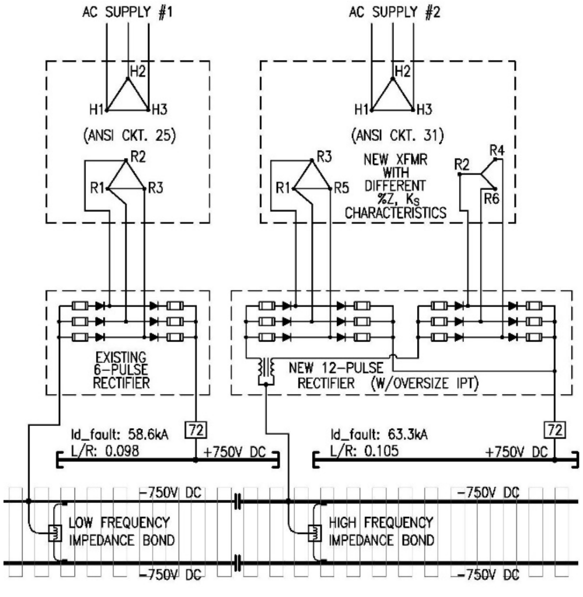

Figure 7: Traction Characteristic Involving Variations (Note that the DC fault current and the rate of rise have been affected by the variation in equipment)

The interactive nature of the AC and DC systems will allow the study engineer to examine the effect of target impedance figures for the anticipated rectifier transformers. While a defined target impedance or a specified commutating reactance figure may be desirable from a rectifier standpoint, it may not be desirable from a total system standpoint. This may be true when the commercial AC source has multiple operating scenarios that may present a significant difference in the short circuit contribution (see Figure 8).

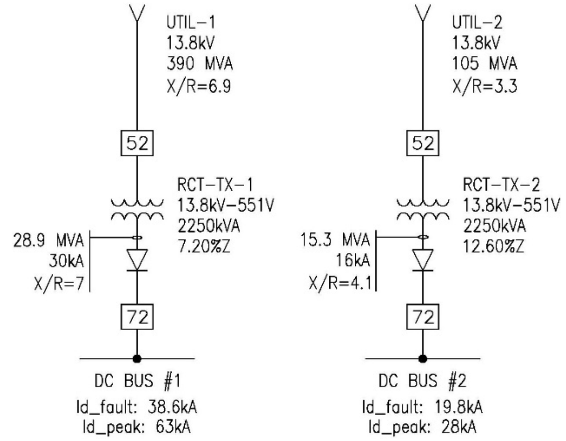

Figure 8: Comparison of Differing Configurations (The DC fault current and rectifier load sharing performance may be affected between the systems)

Reliable train operation depends on the overall traction power system voltage performance. While the distance between traction power substations and the load profile of motive power equipment play the major role in determining this, other sources and rectifier topologies also contribute to the outcome. Whether the motive power supply is AC or DC, the choice of transformers will make a significant difference. Some heavily travelled systems have been known to experience delivery demands approaching 500% of steady-state ratings. Consequently, the specification of proper transformer designs and impedance values can be critical. The load analysis will help the designer ascertain the correct specifications [6].

The inherent voltage regulation between different rectifier topologies (ANSI circuit configurations) is not the same. Thus, an accurate representation of these devices will show where the weak spots may occur. As mentioned above, the AC utility supply may affect the system and can be isolated as the culprit in some scenarios rather than the choice of rectifiers. Sometimes existing traction power substations may have to be relocated or new substations added to accommodate a rail line extension. Given how difficult it is to find real estate in many urban areas, the location of the proposed station may become an issue. The voltage performance analysis can eliminate the guess work before negotiations for property acquisition are attempted.

Rectifier performance and electrical load balance analysis are often calculations left to the proposed manufacturer of the traction power substation equipment. Such models can be complex and time consuming. A manufacturer may be reluctant to perform such an analysis if there is no incentive such as a purchase of the equipment being evaluated. The feasibility study can fill this gap. The principal question is: can the 'new electrical system' work with the existing infrastructure? When accurate models are constructed, this question can be answered with confidence.

One additional item is the effect of secondary winding high-coupling vs. low-coupling factors on multi-winding transformers. High coupling factors certainly help with harmonic current cancellation but may result in rectifier performance different from that of existing rectifiers with low coupling factors. Again, the feasibility study can determine impact of such changes in advance.

XII. CONCLUSION

Traction power systems and the design processes associated with them can be complex. The uncertainties associated with such complexity can be mitigated with a feasibility study using modern analytical tools. However, the tools alone will not suffice. A knowledgeable team equipped with an ample and reliable database of electrical parameters, and a familiarity with manufacturing practices can provide the answers to operating and performance questions before contract documents are prepared. To secure their best interest, transit authorities may find it beneficial to retain a 3rd party engineering consultant to work alongside their in-house engineering resources to formulate an unbiased perspective.

XIII. REFERENCES

[1] *ANSI Standard Practices and Requirements for Semiconductor Power Rectifiers*, ANSI Standard C34.2-1968.

[2] *IEEE Standard for Uncontrolled Traction Power Rectifiers for Substation Applications up to 1500V DC Nominal Output*, IEEE Standard 1653.2-2020.

[3] *IEEE Standard for DC (3200V and below) Power Circuit Breakers Used in Enclosures*, IEEE Standard C37.14-2015.

[4] *IEEE Standard for Preferred Ratings, Related Requirements, and Application Recommendations for Low-Voltage AC (635V and below) and DC (3200V and below) Power Circuit Breakers*, IEEE Standard C37.16-2009.

[5] *IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers*, IEEE Standard C57.18.10-1998.

[6] *IEEE Guide for Rail Transit Traction Power Systems Modeling*, IEEE Standard 1653.3-2021.

[7] *Parameters of DC High-Speed Circuit Breakers*, Railway Research Institute, ul. Chłopickiego 50, 04-275, Warsaw, Poland. MATEC Web of Conferences 180, 06006 (2018).

XIV. BIOGRAPHIES

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