A Test System for Transmission Expansion Planning Studies Meeting the Operation Requirements under Normal Condition as well as All Single Contingencies

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Abstract—**This paper presents a 17-bus 500 kV test system for transmission expansion planning (TEP) studies. An actual 500 kV transmission line geometry was used for the overhead lines of this system. Although many test systems have been introduced for different types of power system analysis, those especially for TEP studies at a transmission voltage level, not distribution voltage level, are few. To the best of our knowledge, the introduced test systems for TEP studies, either those combined with electricity market problems or those used to connect a new load or generation to an existing power grid, consider the studies under only normal condition. However, for TEP studies it is needed that a test system meets voltage drop and line loading limits criteria under normal condition as well as all single contingencies, and in this regard, addressing the latter, all single contingencies, is challenging. This paper addresses this technical gap, introducing a 17-bus test system at a transmission voltage level, 500 kV, that meets requirements under normal condition as well as all single contingencies. In addition to presenting all details of this new test system, load flow results under normal condition as well as the worst single contigency are presented. For studies on the TEP, this test system can be an invaluable resource.**

Keywords—Power system, test system, transmission expansion planning, power system planning, normal condition, single contingency.

I. Introduction

The power industry has undergone a significant transformation, transitioning from a vertically integrated structure to a horizontally integrated open market system. This restructuring has resulted in substantial changes in both demand and generation sides. Even with energy-saving technologies and demand response concepts incorporated into modern power distribution, load demand continues to rise. On the supply side, in addition to giving way to lighter and more flexible generators in place of traditional large generators for electricity generation, the proportion of renewable energy sources is increasing. According to the Western Electricity Coordinating Council (WECC) report on the 2022 Western assessment of resource adequacy [1], the combined demand for the entire Western connection is expected to increase by 11.4 % from 2023 to 2032. From the generation standpoint, the future generation mix is anticipated to undergo significant changes compared to the past. This shift is primarily attributed to the dominance of renewable resources in new generation additions, driven by the state-mandated Renewable Portfolio Standards (RPS) for decarbonization [2]. This requires utilities and power providers to obtain a specified proportion of their electricity from renewable sources. By the year 2032, in a decade-long period, approximately 26 GW of conventional units, mostly the coal and natural gas resources, are going to be retired and 80 GW of new generation mostly governed by solar, wind, and energy storage units will be built in the U.S. portion of western interconnection [1]. These anticipated changes pose several technical challenges in the operation and planning of the future power system. The load and generation changes will alter the power flow pattern in the existing system and may result in potential reliability violations such as stability issues, and system overloading. Upcoming large-scale renewable power plants need to be carefully connected to the primary power grid since the location of the plant and the voltage level at the point of interconnection could affect small signal/transient stability and impact the overall reliability of the system [3, 4].

In this dynamic realm of power systems, the electric power system should have the ability to supply enough electricity reliably and consistently. With the continuous growth in energy demand and increased large renewable sources integration in the primary power grid, it becomes imperative to develop a robust, reliable, and economically viable power grid that can meet present and future requirements. Transmission expansion planning (TEP), long-term decision-making to reinforce the transmission network by adding new transmission lines [5], serves as the backbone of this process, as it involves carefully assessing the existing network and determining the needs of power systems, identifying strategic upgrades and expansions of transmission lines to accommodate increasing loads and enhance grid resilience in the future system, considering a variety of technical, economic, environmental, and power system security constraints [6].

The development of a base test system is crucial in the TEP research, and it serves as a reference model for conducting detailed analysis and assessment related to the expansion of transmission network [7]. Having a base test system, various planning scenarios can be studied regarding different optimization TEP formulations. Additionally, the base case system serves as a benchmark for validating and comparing different TEP approaches considering factors such as cost, reliability, environmental impact, and regulatory requirements.

The technical gap is that a few test systems in transmission

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voltage levels for TEP studies have been introduced [5, 8-11]. Since TEP studies need to be done under normal condition as well as all single contingencies, base test systems first need to be reliable under normal condition as well as all single contingencies. However, the Achilles heel of existing test systems is that they meet voltage drop and line loading limits under only normal condition and not under all single contingencies. In other words, it is unclear whether those test systems also meet the requirements under all single contingencies. Without ensuring this essential point, we cannot rely on the winning scenario resulting from a TEP study, such as connecting a new load or power plant to the base test system, since single contingencies are often done for those expansions and the existing transmission lines adjacent to that new load or generation and not all single contingencies. Moreover, questions are raised about the validity of using a base test system not examined under all single contingencies for a TEP study. In such situations, one must first check if his considered base test system meets the requirements under all single contingencies. If not, he must first fix that base test system and then use it for his TEP studies. Here the issue is that some of these test systems are large-scale ones, so examining all single contingencies is challenging. More complicated than that is fixing that base test system even for a small-scale test system. Because there is no straightforward approach, one should examine different options, such as adding new lines, changing loads and generations, changing shunt reactors or capacitors, etc., in a trial-and-error process to fix the issue of having a test system satisfying operation requirements under normal condition as well as all single contingencies. In this regard, it should be noted that although a change may fix the issue under a specific single contingency, it may lead to violations under normal condition or other single contingencies. Therefore, for each change, one should do load flow under normal condition and all single contingencies, and this is an exhausting task, especially in large networks, which is not guaranteed to reach the solution. This paper aims to address these issues and difficulties.

This paper presents a new test system at transmission voltage level, 500 kV, for TEP studies. The test system meets voltage drop and loading line limits requirements under normal condition as well as all single contingencies. In addition to presenting all details of this new test system, load flow results under normal condition and the worst single contingency are also presented. This test system can be an invaluable resource for TEP research.

II. Information of the Test System

A. Power Network Topology

Fig.1 depicts a single-line diagram of the test system. The test system consists of 17 buses. Bus 1 is a swing bus; buses 3, 6, 8, 10, 12, 13, and 15 are voltage-controlled buses (PV buses); and the rest are load buses (PQ buses). The voltage of buses is 500 kV. The buses in Fig. 1 are considered to be in their geographical locations and regarding this assumption, the length of the transmission lines connecting these buses is accurately measured and presented in Table I. The length of line 7-12 was assumed to be 300 km, and the length of other lines was calculated based on this assumption. It should be noted that line 1-2 includes two circuits and the length presented in Table I for this line, 512.90 km, is the length of each circuit. This is the case for other double-circuit lines shown in Fig. 1.

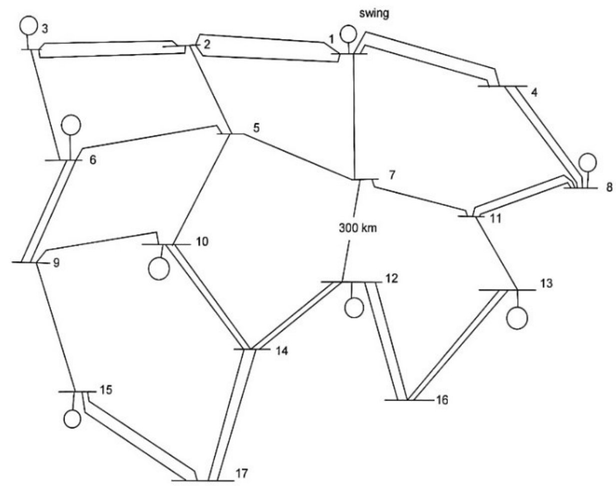

Fig. 1. Single line diagram of the 17-bus test system for TEP studies.

TABLE I. LENGTH OF TRANSMISSION LINES IN THE 17-BUS TEST SYSTEM

Line	Length (km)	Line	Length (km)
1-2	512.90	7-12	300.00
1-4	474.19	8-11	349.09
1-7	370.91	9-10	447.27
2-3	485.45	9-15	398.18
2-5	294.55	10-14	392.73
3-6	349.55	11-13	261.29
4-8	416.13	12-14	348.38
5-6	519.00	12-16	406.45
5-7	435.48	13-16	490.91
5-10	376.36	14-17	403.64
6-9	316.36	15-17	502.70
7-11	387.09		

B. Transmission Line Configuration

Fig. 2 shows the geometrical configuration of 500 kV transmission lines of the test system.

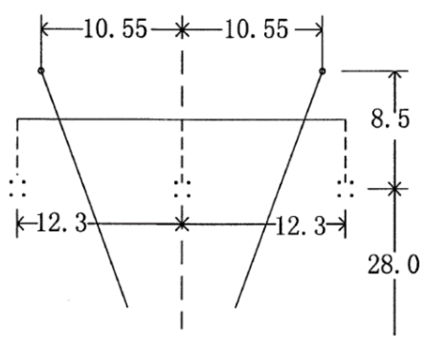

Fig. 2. Geometrical configuration of the 500 kV transmission lines of the test system.

It should be noted each circuit of line 1-2 has the same configuration and arrangement shown in Fig. 2 which is usual in practice for such as voltage levels, instead of two circuits on a tower. In other words, line 1-2 includes two circuits located on separate towers, not on one tower.

As seen, the line has a horizontal (flat) configuration with a phase spacing of 12.3 m at a height of 28 m from the ground and with four bundled subconductors in each phase. This is the configuration of an actual 500 kV line [12]. The conductor type considered for the line is Macaw. Bundle specification and calculated line parameters for this configuration are presented in Table II.

TABLE II. CONDUCTOR INFORMATION AND LINE PARAMETERS FOR THE 17-BUS TEST SYSTEM

Conductor and Bundle Information			**Line Parameters**	
Type	4 × Macaw		R (Ω/km)	0.0228
The outside diameter of each conductor (inches)	1.055		L (mH/km)	0.878
Subconductor spacing (m)	0.45		C (nF/km)	12.975

C. Generation Units and Load Data

For the swing bus, bus 1, $|V_1|$=1.05 p.u. and δ_1 =0. Generating and voltage amplitude information for voltage-controlled buses are presented in Table III. It is assumed that Q_{gmax}= 0.6P_g and Q_{gmax}= –0.3P_g, which is the case for usual synchronous generators in conventional power plants and a usual assumption when doing load flow studies for TEP in practice by utilities.

TABLE III. GENERATION INFORMATION FOR 17-BUS TEST SYSTEM

Bus (Type)	**|V| (p.u.)**	**P_g (MW)**	**Q_{gmin} (Mvar)**	**Q_{gmax} (Mvar)**
Bus 3 (PV)	1.025	2600	-780	1560
Bus 6 (PV)	1.010	2600	-780	1560
Bus 8 (PV)	1.040	2700	-810	1620
Bus 10 (PV)	1.020	2600	-780	1560
Bus 12 (PV)	1.020	2700	-810	1620
Bus 13 (PV)	1.020	2700	-810	1620
Bus 15 (PV)	1.000	2600	-780	1560

The test system consists of a total of 16 loads that are connected to all buses, excluding the slack bus. Each load is assumed to operate at a power factor of 0.9 lagging. Additionally, the system also incorporates shunt reactors that are connected to four buses, buses 2, 4, 14, and 17. The capacity of shunt reactors is 100 Mvar on buses 2, 4, and 14, and 300 Mvar on bus 17. Table IV presents detailed information on the loads and shunt reactors connected to different buses within the system.

III. Power Flow Analysis of the Test System

By analyzing the load flow results for normal operating condition and all contingency situations, planners can identify the areas of congestion, voltage violations, and potential reliability issues. This information is of paramount importance for making informed decisions about where and how to expand the transmission infrastructure. In this section, the load flow analysis for the test system under normal condition as well as single contingency conditions is performed and analyzes whether the test system presents technically feasible solutions.

TABLE IV. LOAD AND SHUNT REACTOR INFORMATION FOR THE 17-BUS TEST SYSTEM

Bus	**Load**		**Shunt Reactor**
	P_L (MW)	**Q_L (Mvar)**	
Bus 2	1725.00	835.45	100 Mvar
Bus 3	1000.00	484.32	---
Bus 4	1585.00	767.65	100 Mvar
Bus 5	1360.00	658.67	---
Bus 6	900.00	435.89	---
Bus 7	1750.00	847.56	---
Bus 8	1000.00	484.32	---
Bus 9	1150.00	556.97	---
Bus 10	1020.00	494.00	---
Bus 11	1155.00	559.39	---
Bus 12	1500.00	726.48	---
Bus 13	1200.00	581.18	---
Bus 14	1770.00	857.25	100 Mvar
Bus 15	1600.00	774.91	---
Bus 16	1460.00	707.11	---
Bus 17	1010.00	489.16	300 Mvar

A. Load Flow Analysis Under Normal Condition

AC power flow analysis problem is formulated as

$$I = Y_{bus}V \tag{1}$$

$$P_i + jQ_i = V_i I_i^* \tag{2}$$

$$P_i = |V_i| \sum_{k=1}^{n} |V_k||Y_{ik}| \cos(\delta_i - \delta_i - \theta_{ik}) \tag{3}$$

$$Q_i = |V_i| \sum_{k=1}^{n} |V_k||Y_{ik}| \sin(\delta_i - \delta_i - \theta_{ik}) \tag{4}$$

where δ_i and $|V_i|$ are the phase angle and magnitude of the voltage at bus i, n is the number of buses in the network, Y_{bus} is the admittance matrix, Y_{ik} are elements of Y_{bus}, and θ_{ik} is the angle of Y_{ik}. P_i and Q_i are the injected real and reactive power into the bus i.

Considered constraints for the power flow analysis are:

$$0.95 \leq |V_i| \leq 1.05\, p.u. \tag{5}$$

$$-0.3P_{gi} \leq Q_{gi} \leq 0.6P_{gi} \tag{6}$$

$$S_{ik} \leq S_{ik}^{max} \tag{7}$$

Eq. (5) represents the voltage constraint in the power system during normal operating and Eq. (6) is the reactive power generation limit for each generating unit, P_{gi}, presented in Table III. Eq. (7) is the apparent power flow limit in the transmission line connecting bus i and k. Maximum power flow, S_{ik}^{max}, is determined by the thermal limit of the mentioned line. Using four Macaw conductors per bundle, the thermal limit of the line is 3×(500 kV)×(4×0.870 kA)=3014 MVA. 80% of the thermal limit, 2400 MVA, is considered the line rating, S_{ik}^{max}.

The Newton-Raphson method is used to solve the power flow problem of Eqs. (1)-(4) with constraint from Eqs. (5)-(7) with the generation and load data presented in Tables III and IV, respectively, in the test system shown in Fig. 1. The PSS/E 35.4 simulator is used to perform the analysis. The results of the load flow analysis under normal operating condition are presented in Table V.

TABLE V. LOAD FLOW ANALYSIS RESULTS FOR THE 17-BUS TEST SYSTEM UNDER NORMAL OPERATING CONDITION

Bus #	Voltage		Generation	
	$\|V\|$ $p.u.$	δ (deg.)	P_g (MW)	Q_g (Mvar)
1	1.050	0.00	2946.9	-1604.8
2	1.050	-12.00	0.0	0.0
3	1.025	12.74	2600.0	-205.5
4	1.050	-13.51	0.0	0.0
5	1.049	-18.29	0.0	0.0
6	1.010	7.93	2600.0	-488.3
7	1.044	-18.29	0.0	0.0
8	1.040	-2.06	2700.0	-550.3
9	1.030	-6.13	0.0	0.0
10	1.020	-7.14	2600.0	-600.6
11	1.048	-13.24	0.0	0.0
12	1.020	-16.19	2700.0	-725.7
13	1.020	-4.49	2700.0	-284.1
14	1.047	-24.15	0.0	0.0
15	1.000	-6.04	2600.0	-194.4
16	1.049	-22.82	0.0	0.0
17	1.050	-24.61	0.0	0.0

As seen in Table V, the per unit voltage at each bus and the reactive power generated by all generating units remain within the specified threshold outlined in Eqs. (5) and (6). The highest line loadings are 31.1% for line 2–3, 30.9% for line 1–7, 30.6% for line 9–10, and 26.6% for line 6–9. The line loading percentage is below 25% for the rest of the lines. These values are considerably lower than the maximum line loading considered for the transmission line. Therefore, the test system meets both voltage drop and line loading limits under normal condition.

B. Load Flow Analysis Under Single Contingencies

A power system is designed to work even if a component goes missing, a situation known as a single contingency. In TEP studies the components taken into consideration for single contingency studies are transmission lines and transformers known as branches, and for our test system, it is losing a transmission line. For load flow under every single contingency, Eqs. (1)-(4) and constraints in Eq. (6) and (7) are still used, however for the voltage drop, the voltage magnitude in all buses should be more than 0.9 p.u., not 0.95 p.u., as follows.

$$0.90 \leq |V_i| \leq 1.05\ p.u. \tag{8}$$

We did load flow analysis for all single contingencies in the test system and the results are summarized in Table VI. Each row represents a specific contingency condition. For example, for the first row, it is assumed that one of two circuits of line 1-2 is out, and for this single contingency, the lowest magnitude of voltage occurs at bus 2, 0.943 p.u., and the highest line loading is for line 1-7, 33.3%.

As seen in Table VI, the worst single contingency is when one of the circuits of line 15-17 is out where $|V_{17}|$=0.900 p.u. Another severe single contingency is when one of the circuits of line 2-3 is out where $|V_5|$=0.904 p.u. In terms of line loading, percentage loadings of 46.1%, 45.8%, and 42.8% are the three highest line loadings when one of line 2–3, one of line 1–7, and one of line 6–9 outages, respectively. For all other single contingencies, the highest line loadings are below 40%. Based on these results, the test system meets the criteria under single contingencies as well.

TABLE VI. SUMMARIZED LOAD FLOW ANALYSIS OF ALL SINGLE CONTINGENCIES FOR THE 17-BUS TEST SYSTEM

Line outage	Lowest Voltage		The Highest Line Loading	
	$\|V\|$ $p.u.$	Bus #	% loading	Line
1-2 (1 line)	0.943	2	33.3%	1–7
1-4 (1 line)	0.934	4	33.4%	1–7
1-7 (1 line)	0.970	7	45.8%	1–7
2-3 (1 line)	0.904	2	46.1%	2–3
2-5	0.958	5	33.7%	1–7
3-6	1.000	15	34.1%	2–3
4-8 (1 line)	0.944	4	31.3%	2–3
5-6	0.935	5	35.5%	2–3
5 -7	0.962	5	30.9%	1–7
5-10	0.924	5	33.8%	5–6
6-9 (1 line)	0.977	9	42.8%	6–9
7-11	0.992	7	32.7%	1–7
7-12	1.000	15	31.4%	1–7
8-11 (1 line)	0.998	11	32.7%	8–11
9-10	0.980	9	31.0%	1–7
9-15	0.991	9	31.0%	1–7
10-14 (1 line)	0.985	14	39.3%	10–14
11-13	1.000	15	32.1%	13–16
12-14 (1 line)	1.000	15	30.5%	1–7
12-16 (1 line)	0.967	16	31.2%	2–3
13-16 (1 line)	0.937	16	34.8%	13–16
14-17 (1 line)	0.945	17	31.2%	2–3
15-17 (1 line)	0.900	17	33.4%	15–17

We did a TEP study on the test system proposed in this paper presented in [13]. We also extended this test system to be able to use under different loadings: peak and dominant loadings [14]. The impact of considering all single contingencies can be seen by comparing this paper with [15] where the test system meets requirements under only normal condition, and not under single contingencies as well. In [13, 15], TEP studies were carried out using the conventional line shown in Fig. 2 compared with using the unconventional HSIL lines developed and discussed in [16-21]. Among the difficulties of designing HSIL lines, live line working may be challenging due to the interaction of maintenance personnel and those compact lines with unconventional bundle arrangements especially in freezing conditions [22-26]. Also

IV. CONCLUSION

In this paper, a 17-bus 500 kV test system was introduced for use in transmission expansion planning (TEP) studies. The Achilles heel of existing test systems for use in TEP studies is that they meet voltage drop and line loading limits under only normal condition and not under all single contingencies and we cannot rely on the winning scenario from a TEP study without ensuring this essential point. This paper addresses this technical gap by introducing the mentioned test system meeting criteria under normal condition as well as all single contingencies. In addition to providing all details of this test system, load flow analysis done by PSS/E for this test system under normal condition as well as all single contingencies were presented. In

TEP studies, the proposed 17-bus 500 kV test system can be of great value as a reference and resource.

References

[1] "Western assessment of resource adequacy", Western Electricity Coordinating Council (WECC), 2022, Available: www.wecc.org/Reliability/2022%20Western%20Assessment%20of%20Resource%20Adequacy.pdf

[2] J. S. Heeter, B. K. Speer, and M. B. Glick, "International best practices for implementing and designing renewable portfolio standard (RPS) policies," Tech. Rep. #NREL/TP-6A20-72798, Apr. 2019.

[3] D. Gautam, V. Vittal, and T. Harbour, "Impact of increased penetration of DFIG-based wind turbine generators on transient and small signal stability of power systems," *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1426–1434, Aug. 2009.

[4] K. N. Nwaigwe, P. Mutabilwa, and E. Dintwa, "An overview of solar power (PV systems) integration into electricity grids," *Mater. Sci. Energy Technol.*, vol. 2, no. 3, pp. 629–633, Dec. 2019.

[5] M. Mehrtash, B. F. Hobbs, and Y. Cao, "A large-scale test system for transmission expansion planning with AC networks model," *IEEE Texas Power and Energy Conf. (TPEC)*, College Station, TX, USA, Feb. 2022, pp. 1–5.

[6] A. J. Conejo, L. Baringo Morales, S. J. Kazempour, and A. S. Siddiqui, *Investment in Electricity Generation and Transmission*. Cham: Springer International Publishing, 2016.

[7] J. Quintero, H. Zhang, Y. Chakhchoukh, V. Vittal, and G. T. Heydt, "Next generation transmission expansion planning framework: Models, tools, and educational opportunities," *IEEE Trans. Power Syst.*, vol. 29, no. 4, pp. 1911–1918, Jul. 2014.

[8] A. Akhavein and B. Porkar, "A composite generation and transmission reliability test system for research purposes," *Renewable Sustainable Energy Rev.*, vol. 75, pp. 331–337, Aug. 2017.

[9] I. Pea, C. B. Martinez-Anido, and B. Hodge, "An extended IEEE 118-bus test system with high renewable penetration," *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 281–289, Jan. 2018.

[10] R. Romero, A. Monticelli, A. Garcia, and S. Haffner, "Test systems and mathematical models for transmission network expansion planning," *IEE Proc. Gener., Transmiss. Distrib.*, vol. 149, no. 1, pp. 27–36, Jan. 2002.

[11] "Electric Grid Test Cases," Available: https://electricgrids.engr.tamu.edu/electric-grid-test-cases/

[12] H. Wei-Gang, "Study on conductor configuration of 500 kV Chang-Fang compact line," *IEEE Trans. Power Deliv.*, vol. 18, no. 3, pp. 1002–1008, Jul. 2003.

[13] B. Dhamala and M. Ghassemi, "Unconventional high surge impedance loading (HSIL) lines and transmission expansion planning," *IEEE North American Power Symp. (NAPS)*, Asheville, NC, USA, 2023.

[14] B. Dhamala and M. Ghassemi, "A test system for transmission expansion planning studies for both normal condition and all single contingencies," *IEEE Open Access Journal of Power and Energy*, submitted for publication, 2023.

[15] B. Dhamala and M. Ghassemi, "Transmission expansion planning via unconventional high surge impedance loading (HSIL) lines," *IEEE North American Power Symp. (NAPS)*, Asheville, NC, USA, 2023.

[16] M. Ghassemi, "High surge impedance loading (HSIL) lines: A review identifying opportunities, challenges, and future research needs," *IEEE Trans. Power Del.*, vol. 34, no. 5, pp. 1909-1924, Oct. 2019.

[17] M. Abedin Khan and M. Ghassemi, "A new unusual bundle and phase arrangement for transmission line to achieve higher natural power," *IEEE North American Power Symp. (NAPS)*, Asheville, NC, USA, 2023.

[18] M. Abedin Khan and M. Ghassemi, "Calculation of corona loss for unconventional high surge impedance loading (HSIL) transmission lines," *IEEE North American Power Symp. (NAPS)*, Asheville, NC, USA, 2023.

[19] M. Abedin Khan and M. Ghassemi, "A new method for calculating electric field intensity on subconductors in unconventional high voltage, high power density transmission lines," *IEEE Conf. Electrical Insul. Dielectric Phenomena (CEIDP)*, East Rutherford, NJ, USA, 2023.

[20] M. Abedin Khan and M. Ghassemi, "Calculation of audible noise and radio interference for unconventional high surge impedance loading (HSIL) transmission lines," *IEEE Conf. Electrical Insul. Dielectric Phenomena (CEIDP)*, East Rutherford, NJ, USA, 2023.

[21] B. Porkar, M. Ghassemi, and M. Abedin Khan, "Transmission expansion planning (TEP)-based unconventional high surge impedance loading (HSIL) line design concept," *IEEE North American Power Symp. (NAPS)*, Asheville, NC, USA, 2023.

[22] M. Ghassemi, M. Farzaneh, and W. A. Chisholm, "Three-dimensional FEM electrical field calculation for FRP hot stick during EHV live-line work," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 6, pp. 2531–2540, Dec. 2014.

[23] M. Ghassemi, M. Farzaneh, and W. A. Chisholm, "A coupled computational fluid dynamics and heat transfer model for accurate estimation of temperature increase of an ice-covered FRP live-line tool," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 6, pp. 2628–2633, Dec. 2014.

[24] M. Ghassemi and M. Farzaneh, "Coupled computational fluid dynamics and heat transfer modeling of the effects of wind speed and direction on temperature increase of an ice-covered FRP live-line tool," *IEEE Trans. Power Del.*, vol. 30, no. 5, pp. 2268–2275, Oct. 2015.

[25] M. Ghassemi and M. Farzaneh, "Effects of tower, phase conductors and shield wires on electrical field around FRP hot stick during live-line work," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 6, pp. 3413–3420, Dec. 2015.

[26] M. Ghassemi and M. Farzaneh, "Calculation of minimum approach distances for tools for live working under freezing conditions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 2, pp. 987–994, Apr. 2016.