Statement of Work

This Research Statement of Work is made and entered into effective the _1st_ day of _January___, 2018 by Eversource Energy Service Company, for itself and as agent for its affiliates, having principal offices at 107 Selden Street, Berlin, CT 06037 ("Company") and UNIVERSITY OF CONNECTICUT ("University") pursuant to the terms of the SECOND AMENDED AND RESTATED SPONSOR RESEARCH AND SERVICES AGREEMENT between Company and University dated May 1st, 2015 (the "Sponsor Research Agreement").

Both Parties agree to participate in Research to be conducted in accordance with the terms and conditions of the Sponsor Research Agreement and this Research Statement of Work, provided however, that in the event of a conflict between the terms and conditions of the Sponsor Research Agreement and this Research Statement of Work, the terms of the Sponsor Research Agreement shall be controlling.

1. Title of Research/Project: HVDC Grid Hardening against Geomagnetic Disturbance (GMD)
2. Research/Project Description: A state of the art research for hardening of Eversource Energy's HVDC systems against GMD and monopole operation of the HVDC system is carried. It includes a detailed modeling of all HVDC system components in EMTP, study of potential geomagnetic induced current (GIC) impacts on the HVDC system, study of ground return currents in ac systems generated by HVDC monopolar operations leading to half-cycle saturation of transformers and model development for a Neutral Current Blocking Device (NCBD) in EMTP. Moreover, a thorough literature review on technology assessment on nanocomposite magnetic material with function of dc bias elimination in power and converter transformers, GIC mitigation strategies and earth model and coast effect for GIC studies is presented.

A. Problem Statement
B. Proposal Objectives
C. Methodology
D. Data Requirements
E. Project Deliverables
F. Project Timetable and Milestones
G. Project Dates - 1/1/18 12/31/19

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A. Problem Statement

Eversource Energy serves electricity to customers in Connecticut, Massachusetts and New Hampshire. These three states along with Maine, Vermont and Rhode Island forms the six states of the northeastern United States knows as New England. To the best of our knowledge, the present and planned HVDC applications in the three mentioned states served by Eversource Energy are as follows.

HVDC applications and flexible alternative current transmission systems (FACTS) have been integrated in the Northeastern United States and Canada power grid for almost 25 years. In this regard, the Multi-Terminal HVDC (MTDC) network interconnects Radisson and Nicolet stations in Quebec and Sandy Pond in Massachusetts in Boston area, the world's first MTDC. Each of these installations includes 2 × 1,000 MW converter groups (CGs) connected with a ±450 kV, 960-mile HVDC line transmitting clean power to New England from a massive hydroelectric complex located in the James Bay area in northern Quebec. These installations, built by ABB (ASEA) and commissioned in 1992 are the conventional HVDC technology: thyristor based, Line Commutated Converter (LCC), also known as Current Source Converter (CSC) type. LCC-HVDC requires heavy and expensive filtering devices to remove the harmonics produced, and hence a LCC station usually has a large footprint. The Cross-Sound Cable which is a ±150 kV, 25 mile, 330 MW HVDC submarine cable between New Haven, Connecticut and Shoreham, Long Island New York having HVDC light technology built by ABB was commissioned in 2002. As one of studied and planned projects, the wind energy up to 15,000 MW in order to import to New England could be achieved from several scenarios through HVDC links as follows. 1) a ±450 kV, 280 mile, 1500 MW HVDC interconnection from Quebec to Millbury, Massachusetts, 2) a ±450 kV, 400 mile, 1500 MW HVDC interconnection from New Brunswick to Millbury, Massachusetts, 3) HVDC submarine Cables along with HVAC network to import 12,000 MW wind energy including 7,500 MW of inland wind and 4,500 MW of offshore wind to New England. Moreover, a 180-190 mile HVDC line has been projected to carry 1,200 MW hydropower from Windsor, Quebec to Deerfield, New Hampshire, with a HVDC converter terminal built in Franklin, New Hampshire.

There is an increasing interest in using clean energies such as hydropower and wind in New England. These energy resources, provided from Quebec, New Brunswick as well as Maine, Vermont and New York states could be more justifiable due to the long-term contracts not adversely affected by electric power markets. HVDC lines provides a desirable option for transmitting bulk power over long distances and HVDC submarine cables may be only technical option for transmitting power generated by offshore wind resources. On the other hand, it has been known that New England is the most geomagnetic disturbance (GMD) susceptible area in the US. A failure rate of 60% of power transformers due to GMD has been reported in New England. The GMD impacts on the HVDC systems are mentioned in the literature but they have not been simulated and investigated in details, to the best of our knowledge.

Solar storms lead to geomagnetic disturbances which, in turn, drive quasi-dc GICs along transmission lines and through transformer windings. GICs cause half-cycle saturation in power transformers that leads to damage and equipment shut down, e.g. production of harmonics,

increasing reactive power demand which cause voltage instability and potentially large-scale voltage collapse, unnecessary relay tripping and hot spots in transformers. Potential geomagnetic disturbance impacts and problems on HVDC systems are as follows.

1. Extra harmonics caused by half-cycle saturation in converter transformer due to GIC in line commuted converter high voltage direct current (LCC-HVDC) systems can lead to commutation failures. It can also cause thermal overloading and tripping of filters and SVCs which normal function of LCC-HVDC systems highly depend on.
2. Transformer saturation can also cause severe disruptions for phase-locked loops (PLLs) used in VSC-HVDC systems.
3. Impedance mismatch induced reflection from the DC side to AC side through the converters may also cause certain harmonic values to be amplified and thus increase the stress on filters protective devices and the grid.
4. Converter transformers in HVDC systems are usually designed as three single-phase transformers. They saturate much faster than three-legged core transformer when subjected to GIC.
5. DC current dissipating from the HVDC converter electrode when operated in the ground return mode (monopole) results in neutral currents in transformers installed in AC system. It can cause the same problems like GIC in AC systems. On the other hand, when this current and GIC occur at the same time the power grid will face more risks.
6. It is well known that the horizontal geoelectric field is amplified in coastal areas, a phenomenon called the "coast effect". The enhancement of the geoelectric field means that GIC also tends to be large in electrical installations located at and near a coast in particular the east coast of the US. This path has also been planned for transmitting 4,500 MW of offshore wind distributed on the coasts of Maine, Massachusetts, and Rhode Island to New England load centers by HVDC submarine cable. The converter stations located at and near the coast of this system are most susceptible installations to the high-amplitude GIC resulted from coast effect.

Due to the mentioned problems, a systematic study is needed to assess potential GIC impacts on HVDC systems operated and planned by Eversource Energy and to develop mitigation methods.

B. Proposal Objectives

The objectives of this R&D assignment are as follows.

1. Identifying potential impacts of GMD on one of HVDC systems, as the case study, operated or planned by Eversource,
2. Identifying potential impacts due to monopole operation of one of HVDC systems operated or planned by Eversource,
3. Producing a guide for Eversource personnel on optimal deployment of blocking devices based on predictive toolbox for GMD impact for HVDC/HVAC systems
4. Producing a comprehensive state of the art report on the coast effect

C. Methodology

In order to fully achieve the objectives of this assignment in the most cost effective manner, we are proposing a methodology that takes full advantage of the previously completed and on-going work by various stakeholders. The deliverables will be suitably organized into the corresponding guides

and a stand-alone complete report with sufficient background material for the benefit of readers with different levels of knowledge and experience. An extensive and comprehensive listing of references and resources will be included with the report, intended to help readers to learn more about the report background. Our methodology and work plan is proposed to comprise of the following main tasks, organized in a phased approach:

Phase 1: This phase includes four tasks as fallows.
Task 1: Literature Search and Utility Surveys
Task 2: Earth Model and Coast Effect
Task 3: HVDC System Model Development

Phase 2: This phase includes three tasks as fallows.
Task 1: Study and Identifying GIC Impacts
Task 2: Model Development to Estimate the Current Entered into the HVAC System Connected to the HVDC System Operating as Monopole
Task 3: Literature Search and Utility Surveys on GIC Mitigation Strategies

Phase 3: This phase includes three tasks as fallows.
Task 1: Study the Impacts of the Monopole Operation on the HVAC system
Task 2: Model Development for a Neutral Current Blocking Device (NCBD)
Task 3: Technology Assessment on Nanocomposite Magnetic Material for mitigating the effect of DC Bias in Transformers
Task 4: Reporting and hand-off planning; Preparing next phase proposal on mitigation, optimization of sitting and sizing for engineering scale-up validation and deployment.

The above listed tasks are described below:

Phase 1-Task 1: Literature Search and Utility Surveys
The main objective of this task is to conduct a thorough and in-depth literature review regarding impacts of GMD on HVDC systems. Moreover, experiences reported by electric utilities worldwide on this topic are reviewed. Some issues which are addressed in this Task are:

- A detailed description of GIC failures occurred on HVDC systems worldwide along with the lessons learned and the mitigation measures acted.
- A detailed description of failures occurred due to the ground return mode (monopole) operation of HVDC system worldwide along with the lessons learned and the mitigation measures acted.
- A detailed mathematical description to address why converter transformers designed as three single-phase transformers are more susceptible than three-legged core transformer when subjected to GIC.
- A detailed description about impedance mismatch induced reflection from the DC side to AC side through the converters, a phenomenon was first detected at Radisson converter station. It

was reported by Hydro Quebec that during a GIC event, 5th and 7th harmonic distortion on the ac side produced excessive 6th harmonic voltage distortion on the dc side, resulting in the failure of an arrester in the dc harmonic filter branch in one pole.

- A detailed description to address how a GIC may cause commutation failures in a LCC-HVDC system
- A detailed mathematical description to address how a GIC may also impact VSC-HVDC systems

To complement the above findings a utility survey (developing a questionnaire) on GIC impacts on HVDC systems is prepared. The reason for this utility survey is to capture the events not reported in literature. However, utilities' involvement in this survey is not a trivial task. The survey questionnaire will focus on seeking utility experience concerning in particular six issues described in A. Problem Statement Section.

Phase 1-Task 2: Earth Model and Coast Effect

Numerical modeling of the effect of GIC in power transmission networks involves two components: geophysical and technological. The geophysical component deals with the calculation of a geoelectric field at locations along the transmission network. The technological component uses the geoelectric field as an input into the system model and calculates the GIC throughout the network. In this regard, earth resistivity is a key parameter to calculate GIC. Because the frequencies of natural geomagnetic variations are very low, ranging from mHz to several Hz, the penetration depth into Earth's interior is very high (up to several 100s km depth). Thus deep geological conditions in the crust and mantle affect the surface geoelectric field. Although the Earth's internal structure can have a complex three-dimensional distribution of electrical resistivity, a 1D model provides a useful first-order approximation for modeling gross resistivity structure and its effect on surface electric field in a particular region. In this Task 1D earth resistivity model for New England form EPRI Technical Report no. 1026430 is assessed. In that Technical Report, nineteen models for selected continental United States physiographic areas were prepared, as well as five models covering parts of Alaska.

On the other hand, in coastal areas the vicinity of the ocean-land interface implies that a 1D model is not correct due to a phenomenon called the "coast effect". In this task, a state of the art report regarding the qualitative understanding and quantitative description of the amplification of the geoelectric field in coastal areas are presented. In this regard, precise knowledge of the magnitude of the amplification and of the distance how far away from the coastline the amplification extends requires a better earth conductivity model. Regarding practical power engineering work on GIC issues, the many versatile 2Dand 3D Earth/ocean models, which are published in geoelectromagnetic literature and which generally aim at investigating the ground structure and geology, are not the most appropriate. With an emphasis on GIC applications the models and techniques for a quantitative investigation of the coast effect on the geoelectric field are reviewed.

Phase 1-Task 3: HVDC System Model Development

In this Task a detailed model of one of HVDC systems operated or planned by Eversource Energy as the case study in EMTP is developed. The model includes HVDC converter station, reactive power compensation devices such as SVC, filters, converter transformers and HVDC overhead line

or cable. To model this system, it should be noted that the most vulnerable components in this system to the GIC are the converter transformers. Since GIC appears as quasi-DC and can last for minutes to hours, it stresses the converter transformers into the state known as half-cycle saturation. Half-cycle saturation is considered as the root cause of nearly all GIC-related problems in the system. The associated phenomena involve very slow transients, in mHz range, with representing the high magnitudes of even and odd harmonics of power frequency. As a result, the transformer response involves both nonlinear and frequency dependent effects. On the other hand, the converter transformers designed often as three single transformer saturate much faster than three-legged core transformer when subjected to GIC. Thus, a sophisticated model of converter transformer is developed for such study. In this task the impact of variations in the transformer core construction and design parameters on its saturated behavior and the resulting reactive power absorption, when subjected to GIC, is studied. Furthermore, the transformer dynamics during the slow transient of the GIC variations and polarity reversal are studied.

Phase 2-Task 1: Study and Identifying GIC Impacts

After carrying out Phase 1-Task 2 and Phase 1-Task 3, potential GIC impacts on the case study are studied. For example, the relationship between GIC and harmonics generated by converter transformer half-cycle saturation is investigated and according to simulation results we can determine minimum amplitude of GIC that can lead to a commutation failure in a LCC-HVDC system as well as thermal overloading and tripping of filters and SVCs used in the HVDC system.

Phase 2-Task 2: Model Development to Estimate the Current Entered into the HVAC System Connected to the HVDC System Operating as Monopole

The earth electrode for the Radisson HVDC converter station is at the Duncan site is approximately 40 km from the Radisson. Due to high ground resistivity in this region, some percentage (up to 15%, measured by Hydro Quebec) of the direct current injected at the electrode station returns to the ac system through the neutral of the power transformers located at Radisson. The resulting saturation of the transformers leads to generate harmonics, which subsequently propagate in the main grid. Therefore, not only due to GMD but also in the ground return mode operation, HVDC systems cause a dc-bias in the magnetizing current of transformers. On the other hand, when the aforementioned currents occur at the same time, the power grid will face more risks. The mechanism of ground return current due to GIC has been well established. However, ground return current due to dissipating from the HVDC grounding electrode has not been modeled so far. In this task, we develop a mathematical model to determine what percent of the direct current injected at the electrode station returns to the ac system.

Phase 2-Task 3: Literature Search and Utility Surveys on GIC Mitigation Strategies

Mitigation strategies of the GIC entering the HVDC and HVAC systems include blocking, reducing or compensating methods. For example, a neutral current blocking device (NCBD) for transformer neutrals was studied by IREQ and TransEnergie, two divisions of Hydro Quebec and commissioned to mitigate GIC as well as dc current flow due to monopole operation of Radisson-Sandy Pond HVDC system. NCBDs with various overvoltage protection schemes and bypass techniques were

studied by Hydro Quebec and its divisions. In another attempt, TransEnergie in collaboration with GE, developed and installed dc current-blocking series capacitors in the middle of 735-kv transmission lines in the vicinity of the Radisson substation to block the flow of the neutral dc current caused by the HVDC monopole operation through the main network. These dc blocking series capacitors have also played a positive role in keeping Radisson substation in operation during magnetic storms by reducing the GIC flowing into the ac lines via grounded transformer windings. A comprehensive literature review of all GIC mitigation strategies is presented in this Task.

Phase 3-Task 1: Study the Impacts of the Monopole Operation on the HVAC system
After carrying out Phase 2-Task 2, we study the impacts of dc current returned to the ac system due to monopole operation of HVDC system. The impact is mainly half-cycle saturation in power transformers near HVDC grounding electrode station.

Phase 3-Task 2: Model Development for a Neutral Current Blocking Device (NCBD)
A detailed model of a neutral current blocking device (NCBD) as a blocking strategy is developed in EMTP. Then by using the model, the influence of its size on the HVDC and HVAC system affected by GIC is studied. In this task, only one NCBD is studied. For next proposal and project, we will propose to study more than one NCBD in a study network in order to develop a methodology to determine the optimal placement of NCBDs for various objective functions.

Phase 3-Task 3: Technology Assessment on Nanocomposite Magnetic Material with Function of DC Bias Elimination in Transformers
Nanocomposite magnetic materials have attracted considerable research interest. The microstructure of a nanocomposite magnet is composed of a mixture of magnetically hard and soft phases. Recently some nanocomposite magnetic materials e.g. $Fe_3B/Nd_2Fe_{14}B$ containing Cr and Co to eliminate dc bias in transformers have been researched. This is a promising technology in particular for the power transformers and the converter transformers located in the areas experiencing the high amplitude of GIC. In this task a state of the art report about technology assessment on nanocompsite magnetic materials with function of dc bias elimination in transformers is presented.

Phase 3-Task 4: Reporting, Hand-off Planning and Preparing Next Phase Proposal
In this task, in addition to reporting and hand-off planning, we prepare next proposal regarding feedbacks from Eversource Energy. Topics proposed for further research include model development for the optimal sitting and sizing of mitigation devices such as NCBDs as well as engineering scale-up validation and deployment.

D. Data Requirements
It is proposed that one of HVDC systems operated or planned by Eversource Energy, as the case study, is modeled. Therefore, we need detailed information of the system.

E. Project Deliverables

1. A detailed EMTP modeling of one of the HVDC systems operated by Eversource, interconnected with HVAC network, to assess the impact of GIC as well as the mitigation of GIC by various techniques including neutral current blocking.
2. A state of the art report on the earth resistivity model of New England for GIC studies as well as coast effect
3. A framework on (HVDC) grid hardening against GMD
4. Progress reports as well as summary of the conclusions and recommendations for future research

F. Project Budget and Schedule

Budget

Phase#	Month	Cost ($)
Phase 2	12	$50,000
Phase 3	12	$50,000
Total	24	$100,000

A detailed description of the above budget based on the tasks proposed of each phase is presented in the following tables. The follow on phases (2 and 3) will be awarded based on the execution and delivery of Phase 1 deliverables and updated proposals will be needed for those two phases.

Phase #	Project Tasks	Month	Cost ($)
Phase 2	Task #1	6	$25,000
	Task #2	4	$17,750
	Task #3	2	$7,250
Total		12	$50,000

Phase #	Project Tasks	Month	Cost ($)
Phase 3	Task #1	4	$17,000
	Task #2	5	$18,000
	Task #3	2	$11,500
	Task #4	1	$3,500
Total		12	$50,000

For this project, we propose a sum price of $100,000.

Schedule

We expect to complete the project within 36 months of project initiation by Eversource Energy Center.

Phase#	Task#	Month																																	
		First Year												Second Year												Third Year											
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
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