Simultaneous DC and AC Simulation of GMD Impacts in a Power System

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Abstract−Geomagnetic disturbances (GMD) affect power systems by causing transformer saturation. The primary impacts of transformer saturation are increased harmonic current injections and var losses, which may lead to loss of high-voltage transformers and/or voltage collapse. The investigation of GMD risks and mitigation strategies requires accurate modeling of a GMD. Benchmarks for such studies are rare. This paper proposes an Electromagnetic Transient (EMT)-type benchmark for GMD studies which is based on a modified version of the IEEE 39-bus benchmark; it includes several features found in a real network that are relevant to GMD studies such as: different voltage levels; multiple transmission lines with different orientations; two- and three-winding transformers; transformer models with on-load-tap-changer functionality and realistic nonlinear magnetization branch models for harmonic analysis and var consumption studies; synchronous generator models with realistic saturation data and over-excitation limiter functionality for voltage regulation and voltage collapse studies; reactive power equipment, LV transformers and feeders; and a generic model of geoelectric field.

I. Introduction

Geomagnetic disturbances (GMDs) have received considerable research attention lately due to their impact on pipelines, telecommunication grid, and power transmission grids [1]-[4]. A GMD is a result of the interaction of solar coronal mass ejections with Earth's magnetosphere-ionosphere which produces an ionospheric current, called electrojet. This current perturbs Earth's geomagnetic field, inducing a slowly varying voltage potential known as geo-electric field (GEF) at Earth's surface and resulting in low frequency (0.1mHz-1Hz) geomagnetically-induced current (GIC) to flow through the neutral of grounded transformers into a power system. There are two main risks associated with a GMD: the first is the possible damage of high-voltage transformers and the second is the loss of reactive-power support and voltage collapse [5][6].

In electrical systems, a GMD can be represented by a dc source. When a GIC flows through transformer windings, it creates a flux offset that can drive the core into deep saturation for one-half of the power cycle. The primary impacts of such saturation are increased harmonic current injections and var losses. Such an increase in reactive loading, which is due to the increase in the fundamental component of the exciting current, may lead to voltage regulation problems, transmission line disconnection in case of TC/line protection mis-operation, and voltage collapse [7][8].

Power utilities must investigate the risks of a GMD and develop mitigation strategies. Most investigations concern the protection of power transformers [9], the misoperation of protective relays [10] , and impact on system stability [8][11]. Due to the presence of the quasi-dc current, the simulation of a GMD includes dc and 60Hz frequency components. Most GMD studies have traditionally been conducted using transient stability type programs.

The work presented in this paper is based on the more accurate electromagnetic transient (EMT) analysis approach using EMTP [12]. This approach solves the dc and ac components simultaneously using an iterative solver for the nonlinear magnetization branch of transformers. The objective of this paper is to propose a new EMT-type benchmark, based on a modified version of the IEEE-39 benchmark [14]-[16], which is suitable for GMD studies. The proposed benchmark includes several practical features relevant to GMD studies such as: different voltage levels; multiple transmission lines with different orientations; two- and three-winding transformers; transformer models with on-load-tap-changer (OLTC) functionality as well as realistic nonlinear magnetization branch models for harmonic analysis and var consumption studies; synchronous generator models with realistic saturation data and over-excitation limiter (OEL) functionality for voltage regulation and voltage collapse studies; reactive power equipment; and a generic model of geoelectric field (GEF). Compared to the existing GMD benchmarks in the literature [13], the proposed benchmark contains more modeling details including nonlinear transformer core and machine control, thus enabling a wider range of GMD studies including: the impact of GMD on reactive power equipment; harmonics analysis; the response of machine control to a GMD, and the var consumption of distribution transformers under a GMD. The complete network has been modeled at circuit level with necessary details.

II. The proposed benchmark

The proposed benchmark is a modified version of the IEEE-39 [14] system developed in EMTP and shown in Fig. 1. The benchmark embeds 10 generator-transformers and 20 load-transformers. The nominal rated power of transformers has been calculated from the initial 100 MVA base data (the original IEEE-39 benchmark data were in pu). The line lengths have been calculated from typical positive sequence impedances of a 500kV line. Constant-parameter (CP) line

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models have been used (in lieu of frequency dependent (FD) or wideband models) to reduce computational time. FD line model is necessary for such studies as harmonic calculation under GIC. A future work is to develop a version of the benchmark including FD line models. The change of line models from CP to FD is not expected to impact the GIC, reactive-power, and voltage collapse results of this paper, but may significantly influence harmonic results. All loads have been modeled using their exponential representation.

Synchronous machine (SM) models include automatic voltage regulators and governors (AVR/GOV). The AVR control includes an over-excitation-limiter (OEL). The SMs have been modeled with corresponding d-axis saturation curves and all necessary parameters to accurately represent their transient response. The generators are interfaced to the grid through Yd transformers using single-phase unit models.

In addition to adaptation for detailed EMT-type simulations, the IEEE-39 benchmark has been modified to include specific components for GMD studies. The objective is to develop a complete and accurate benchmark for studying the cumulative effect of supplementary var production (ΔQ) and the impact thereof on voltage regulation with the possibility of voltage collapse. The following are the main modifications with respect to the original IEEE-39 [14]:

- The zero-sequence resistance R_0 of transmission lines has been set at the positive-sequence resistance R_1; the reason is that GIC is essentially a zero-sequence phenomenon. This approach has been verified with more accurate, but significantly more time-consuming, FD transmission lines models. It should be mentioned that typically R_0/R_1=10 which is true at 60Hz but not at dc frequency where the dc resistance R_{dc} is close to R_1 at 60Hz. All transmission lines are continuously transposed (balanced). The line orientations (north-south and east-west) have not been provided in the original IEEE-39 benchmark data and have been arbitrarily set by the positions of line terminals. Line orientation is important for obtaining correct dc flows in lines and transformer neutrals;
- The GEF has been modeled by a dc voltage source injected in series with transmission lines;
- The transformer magnetization curves have been adopted from field test measurements conducted on a single-phase shell-form 300MVA 765kV/120kV transformer [17];
- Loads are placed on the 25-kV side of Yd and Yyd transformers;
- OLTC has been included to study the impact on voltage regulation and voltage collapse; Yyd and Yd transformers have been modeled as three single-phase units.
- All transformers have been connected to a grounding resistance denoted by R_{ground} calculated as

$$R_{ground}^{-1} = R_{grid}^{-1} + R_{ctpAll}^{-1}, \tag{1}$$

where R_{grid} denotes the grounding grid resistance and R_{ctpAll} signifies the equivalent impedance of tower counterpoise of all lines connected to the substation. In the model, R_{grid} has been arbitrarily chosen between 0.5Ω and 1.5Ω whereas R_{ctp} has been fixed at 1.25Ω.

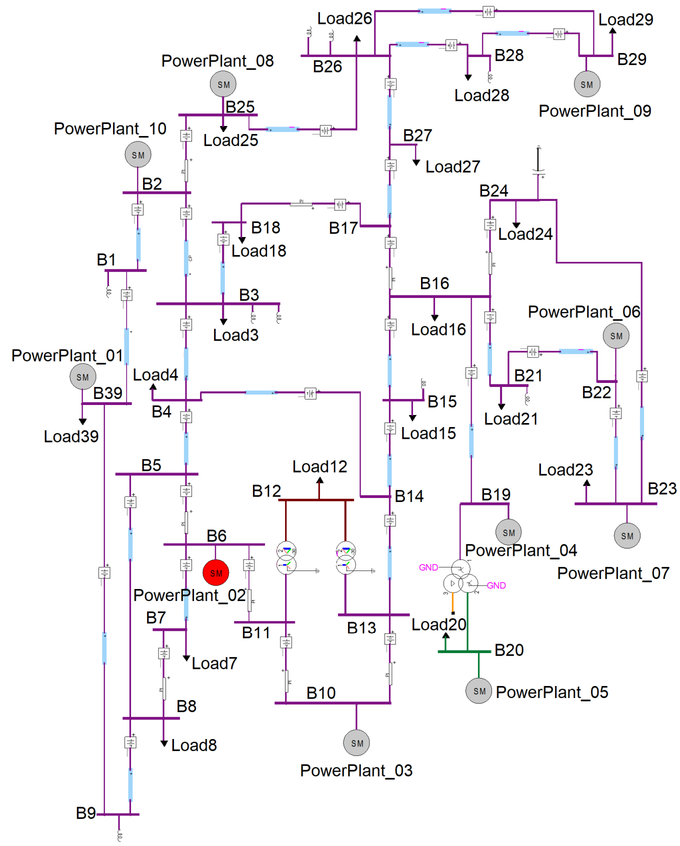


Fig. 1. The IEEE-39 benchmark [14] modified for GMD studies.

III. GEF Model

In Canada, GEF data can be found on the Natural Resources Canada website [19]. Plots of time-varying GEF estimated from one-minute variations of the geomagnetic field are available for all Canadian magnetic observatories. These plots provide E_x (northward electric field) and E_y (eastward electric field) in mV/km. The proposed benchmark models the GEF using a look-up table which generates E_x and E_y signals; the output of this table is then fed to all dc injection devices on transmission lines. This approach can be used to generate any desired functions with unlimited number of field vectors, if necessary.

The dc injection devices are controlled dc sources inserted at 34 line locations. The dc voltages are calculated based on

$$\theta(t) = L_\theta - GFA(t) \tag{2}$$

$$V_{dc}(t) = V'_{dc}(t)\ell\cos(\theta), \tag{3}$$

where θ is the difference between L_θ, the angle of the two extrema of the line, and GFA, the GEF angle; these two angles must be defined with respect to the same reference north-south 0° axis. In (3), $V'_{dc}(t)$ represents the GEF magnitude per unit length and ℓ is the substations distance which has been assumed to be 80% of the line length [15]. Thus, to calculate the dc source voltages, one only needs the substations distance and their orientation; the values of these parameters match those of [15] and hence are not repeated in this paper.

IV. Var Consumption Measurement vs. Calculation

As mentioned, the primary impact of a GMD on an electric system is increased var consumption. Hence, an essential aspect of a GMD study is the measurement of such var losses. During a GMD, the electric system is in a nonsinusoidal state due to the presence of the quasi-dc currents. This section presents two methods for modeling var losses due to a GMD.

A. Measurement Method 1(M1)

Method 1 is based on finding the reactive power consumption in the magnetization branch of transformers; thus, the fundamental frequency component of voltage and current of the magnetization branch are measured, and var consumption is calculated based on

$$Q_{GMD}(t) = V_a I_{ma} + V_b I_{mb} + V_c I_{mc}, \tag{4}$$

where V_a, V_b, V_c, I_{ma}, I_{ma}, and I_{ma} represent the fundamental frequency components of terminal node voltage and the magnetization currents of the nonlinear inductance, respectively.

B. Calculation Method 2(M2)

Method 2 is an empirical method proposed by [23] and employed in [24] which measures GMD var losses based on the following equation

$$Q_{total} = kI_{GIC} + Q_0, \tag{5}$$

where Q_{total} represents the total var consumption during a GMD, k is a constant parameter which depends on the transformer core design and the voltage level of high voltage transformer winding normalize to 500kV, I_{GIC} denotes the GIC current flowing in the transformer neutral per phase, and Q_0 is the var consumption in normal operating conditions (no GMD). Based on (5), the var consumption due to GMD can be directly calculated as

$$Q_{GMD} = kI_{GIC}. \tag{6}$$

V. Simulation of var Losses and Harmonics

This section presents the simulation of a GMD in the proposed IEEE-39-based benchmark. The first case considers a constant GEF of 2V/km; GEF is never constant in reality, and the proposed benchmark can simulate a user-specified time-varying GEF waveform. The choice of a constant GEF in this section is for illustration purposes.

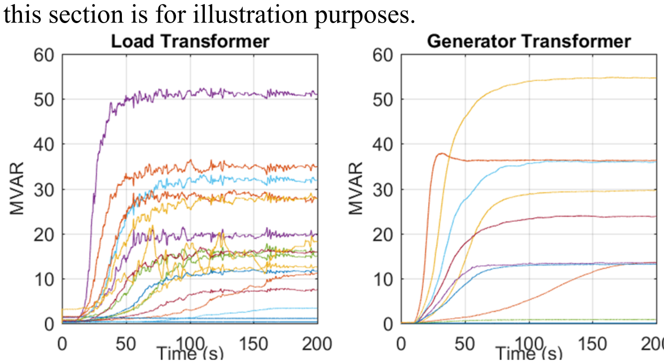


Fig. 2. The var consumption of load and generator transformers of the proposed benchmark under GEF=2V/km.

Fig. 2 shows the reactive power consumption measured with M1. The response time (90%) required to reach full saturation varies from 20-100s.

As mentioned earlier, another impact of GMD is increased harmonic current injections due to transformer saturation. If sufficiently high, such increased harmonic content may cause thermal problems and lead to transformer failure. Basically, a GMD causes a transformer to act as a current source injecting harmonic currents into the grid; the amplitude of these harmonics is independent of transformer capacity. Consequently, the neutral current of the transformer will include a dc component as well as other harmonics. In the proposed benchmark, this dc current has been measured using a second order low-pass filter with a cut-off frequency of 0.2Hz and a damping factor of 0.46.

Fig. 3 shows the time variation of the neutral current harmonics of sample transformers measured by applying a fast Fourier transform (FFT) on the neutral current of the studied transformer. Since this is the neutral current, it contains only the triplen harmonics. The 3rd harmonic of the neutral current is an indicator of a GMD event similar to the 2nd and 4th harmonic current on the primary side.

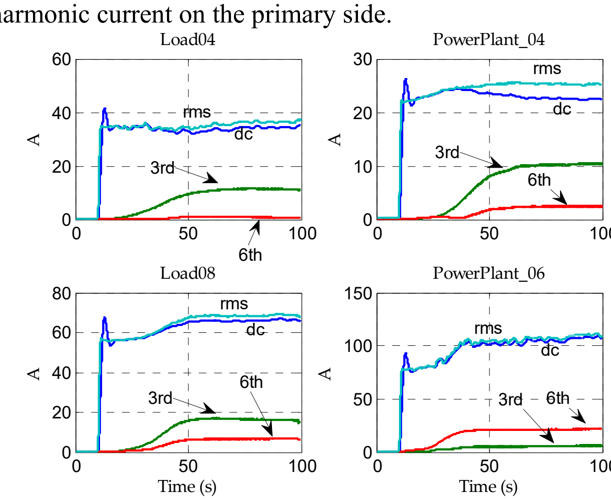


Fig. 3. Harmonics components of the neutral current of transformers.

An impact of increased harmonic injection is the possible tripping of reactive power equipment due to excessive harmonics which may lead to loss of voltage support. The next section studies the impact of GMD on the capacitor bank on bus B24 of the proposed benchmark.

A. Shunt capacitor harmonics measurement

The objective of this section is to determine whether the 92MVar shunt capacitor on bus B24 of the proposed benchmark may trip due to excessive harmonics during a GMD. To that end, the proposed benchmark has been subjected to four GMD events corresponding to four GEF levels of 1V/km, 2V/km, 5V/km, and 10V/km, and the harmonic content of the capacitor current has been measured in each case.

A measure of harmonic content is the Total Harmonic Distortion (THD). This paper uses the IEC standard definition of THD [25] given by

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_{nrms}^2}}{I_{rms}}, \tag{7}$$

where

$$I_{rms} = \sqrt{\sum_{n=1}^{\infty} I_{nrms}^2}. \tag{8}$$

This section focuses on the 2nd, 3rd, 4th, 6th, and 8th current harmonics. Table 1 presents the results of harmonic analysis. As shown, THD increases as the GEF magnitude is increased; THD becomes more significant for GEF>2V/km.

To determine whether this increased harmonic content may result in the tripping of the shunt capacitor, this paper uses clause 20 of the IEC 60871 standard [26] which recommends a harmonic overcurrent limit of 15% for 5min in addition to the fundamental component overcurrent limit of 20% for 5min. As shown in Table 1, the THD values of current exceed these limits for two GEF magnitudes of 5V/km and 10V/km; in these two cases, the components of the capacitor bank may fail causing the protection to open the capacitor bank breaker.

It should be mentioned that accurate harmonic analysis requires the representation of transmission lines, especially those close to the studied equipment, by their FD models. The reason is that FD line models provide more damping on higher frequencies including 2nd and 4th harmonics compared to PI or CP line models. This paper, however, uses CP line models since the original IEEE-39 benchmark does not provide FD line data (only line impedances have been provided). The authors are presently working to add FD line models to the proposed benchmark using the data of a typical 500kV tower; the results will be reported in future publications.

Table 1. Harmonic content of the capacitor bank current.

GEF magnitude (V/km)	1	2	5	10
I_{120Hz}/I_{60Hz} (%)	2.7	7.2	9.9	13.2
I_{180Hz}/I_{60Hz} (%)	1.9	3.5	7.7	8.2
I_{240Hz}/I_{60Hz} (%)	4.5	6.3	14.6	18
THD (%)	12.1	12.8	27.4	29.2

VI. Distribution transformers

Due to transformer connection, the distribution lines are dc-decoupled from the high voltage grid. It is important to determine the order of magnitude of var consumption during a GMD from 100 to 1000 distribution transformers rated from 25kW to 100kW on each distribution line. This section studies var consumption of distribution transformers using a test distribution network shown in Fig. 4. In this study, the transmission grid has been represented by a 120kV ideal voltage source. Thus, the distribution system has been studied in isolation from the proposed benchmark since the objective is only to determine the order of magnitude of supplementary var consumption of distribution transformers. The distribution network model consists of a primary 60km line with 12×5km branches emanating from the primary line, each 5km apart from another on the primary line; each branch consists of 10×500m lines. Fig. 6 shows the content of the subcircuits connected to 100m lines of each branch (square shapes in Fig. 4). There is a total of 360 single-phase transformer units rated at 100kVA and loaded at 30kW (typical value).

To model the saturation characteristic of the distribution transformers, this paper has used the measurements conducted at Hydro-Quebec [18] on more than 20 transformers (see 6 tests shown in Fig. 5a) to obtain an average saturation characteristic as shown in Fig. 5b. All distribution transformers adopt this saturation curve.

A dc voltage source has been added in series with each 500m line; the value of the dc voltage has been calculated from (3); L_θ is increased with an arbitrary step of $12°$ for each 500m section; this geometric topology is an arbitrary choice. This approach limits the relation between the GFA and transformer saturation. A zigzag grounding bank (GB) has been utilized in the distribution network of Fig. 4 to absorb the current resulting from unbalanced loads. The thermal limit of this bank is 250A. The loads are lightly unbalanced which results in a current of 35A (60Hz) circulating in the GB. Under a GMD, the third harmonic currents generated by all single-phase transformers flow in the GB and augment its rms current. Due to the increased current, the GB becomes the weakest link of the system; this large circulating current may damage the GB in the absence of proper protection.

A GMD with a GEF magnitude of 2V/km has been applied at 2s. Fig. 7 shows the simulation results of this test case. In Fig. 7, the real and reactive powers have been measured after the GB (see the measurement point PQ in Fig. 4). Fig. 7 further depicts the rms current of the GB as well as the individual 60Hz and 180Hz components (in rms).

To find a measure of the var consumption of distribution transformers versus GEF magnitude, the test distribution system has been tested with GEF magnitudes of 1V/km, 5V/km, and 10V/km in addition to the 2V/km case. Table 2 presents a summary of the results of this case study under four different values of grounding resistance R_g shown in Fig. 6. The first line of this table is the highest current in the neutral of 360 transformers, the second line is the 180Hz component (rms) of I_n in the GB, and the third line is ΔQ (difference in reactive power between input and output) measured at the PQ location shown in Fig. 4.

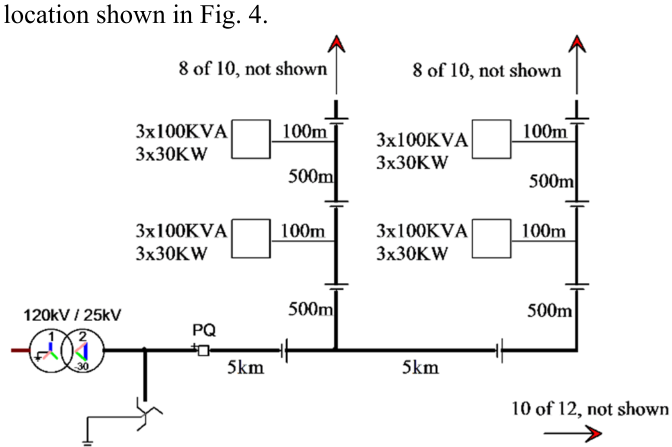
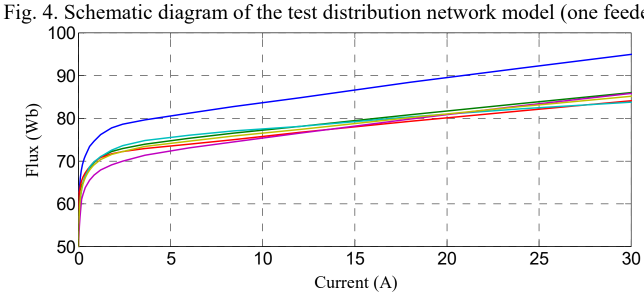
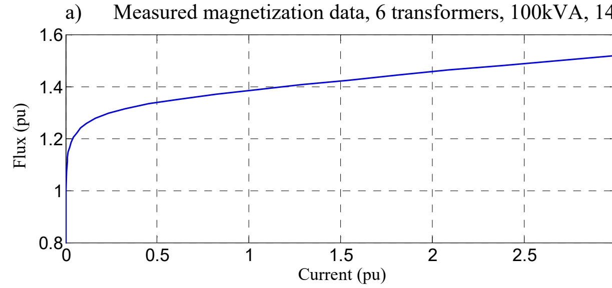


Fig. 4. Schematic diagram of the test distribution network model (one feeder).



a) Measured magnetization data, 6 transformers, 100kVA, 14.4kV.



b) Average magnetization curve used in this paper.

Fig. 5. Magnetization data of distribution transformers.

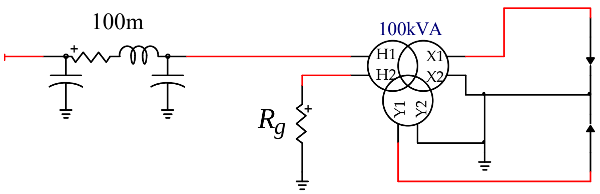


Fig. 6. The single-line diagram of the subcircuits connected to 100m line sections of Fig. 4.

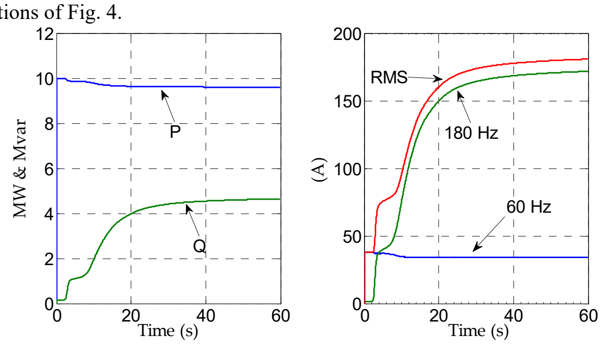


Fig. 7. Real and reactive power flow into the test distribution system (left) and the GB current (right).

Table 2. GMD impact on distribution transformers.

GEF	1V/km	2V/km	5V/km	10V/km
$R_g = 500\,\Omega$ ($\rho = 2000\ \Omega$m, $L = 3.5$ m, $r_0 = 0.01$ m)				
I_n max, dc & rms, (A)	≈ 0	<0.05	0.1&0.1	0.2&0.2
$I_{n_{rms}}$, GB, 180 Hz, (A)	≈ 0	5.0	15.0	30.0
ΔQ (MVar)	≈ 0	0.1	0.4	0.7
$R_g = 50\,\Omega$ ($\rho = 200\ \Omega$m, $L = 3.5$ m, $r_0 = 0.01$ m)				
I_n max, dc & rms, (A)	≈ 0	0.2&0.2	0.5&0.5	1.1&1.4
$I_{n_{rms}}$, GB, 180 Hz, (A)	≈ 0	28.0	65.0	110.0
ΔQ (MVar)	≈ 0	0.6	1.5	3.0
$R_g = 5\,\Omega$ ($\rho = 20\ \Omega$m, $L = 3.5$ m, $r_0 = 0.01$ m)				
I_n max, dc & rms, (A)	0.2&0.2	0.5&0.5	1.4&2.0	2.8&4.6
$I_{n_{rms}}$, GB, 180 Hz, (A)	34.0	85.0	180.0	280.0
ΔQ (MVar)	0.75	2.0	5.0	9.1
$R_g = 2\,\Omega$ ($\rho = 7.5\ \Omega$m, $L = 3.5$ m, $r_0 = 0.01$ m)				
I_n max, dc & rms, (A)	0.4&0.4	1.1&1.4	2.7&4.4	5.5&9.2
$I_{n_{rms}}$, GB, 180 Hz, (A)	60.0	135.0	260.0	357.0
ΔQ (MVar)	1.3	3.3	8.1	15.0

In this case study, the resistance R_g has been calculated using the following formula [20]

$$R_g = \frac{\rho}{2\pi L} \ln\left(\frac{r_0 + L}{r_0}\right) \tag{9}$$

where ρ is the earth resistivity in Ωm, L is the rod length in meters, and r_0 is the rod radius in meters.

The results of Table 2 have been obtained for a total load of 10MW. Applying linear extrapolation, one can estimate the var consumption of distribution transformers for each 1000MW of load. For example, for $R_g = 5\,\Omega$, ΔQ varies between 75MVar and 500MVar as the GEF varies between 1V/km to 5V/km, respectively. This extrapolation cannot be generalized since the GMD level depends on the geographical location.

The above calculations have been performed for 14kV (line-to-ground) lines; for other voltage levels, ΔQ can be proportionally scaled since ΔQ is proportional to nominal voltage; the reason is that transformers can be regarded as current sources during a GMD.

VII. Voltage Collapse Case Study

When the operating point of a power system is close to voltage collapse, the saturation of transformers may lead to voltage collapse. Voltage collapse depends on such factors as initial operation point (on the PV curve) and loss of var control devices such as SVCs, synchronous compensators, and capacitor banks. In networks with long lines, the tap changer operation may also have a significant impact; other networks may be more sensitive to OEL operation. The omission to remove shunt reactors by the operator could also contribute to voltage collapse which can be avoided by designing an automatic control action. The accurate simulation of a voltage collapse event requires performing simulations within an EMT-type program.

This section presents a voltage collapse case study using the proposed benchmark. As mentioned, the transformer models include OLTC with a time delay of 10s per tap and the generator models include magnetic saturation. Table 3 presents the OEL parameters of generators. In this table, the values of the field current I_f have been obtained from steady-state solution and $I_f^{\lim}$ signifies the current limit. Table 3 further presents the limiter integrator time delays. The AVR model is ST1A [21]. The governor model is not important in this study, but the IEEEG1 model [22] has been adopted for all generators. The generator models also include a speed protection scheme which disconnects the machine in the event of loss of synchronization; this device has been set to 1.01pu (frequency).

Table 3. OEL parameters.

Power plant ID	I_f (pu)	$I_f^{\lim}$ (pu)	OEL setting (all)	
1	1.09	N.A.	$I_f / I_f^{\lim}$	time(s)
2	2.53	2.60	102%	120
3	2.38	2.50	105%	95
4	2.24	2.40	110%	74
5	4.19	4.30	115%	60
6	2.38	2.40	125%	40
7	2.20	2.30	138%	28
8	1.93	2.25	160%	20
9	2.12	2.20	210%	10
10	1.30	2.25		

Conducted simulation tests show that voltage collapse may occur even with simplified constant impedance load models; however, this study assumes the worst-case summer load conditions with Np=1 and Nq=1.8 [31]. It should be mentioned that OLTC moves the load characteristic closer to the constant-power characteristics (Np=0 and Nq=0).

A. *Simulation results*

The proposed benchmark has been subjected to a GMD reported in [27] which uses GEF estimation based on a mathematical model of the earth conductivity near Ottawa city, Canada on March 13 and 14, 1989. Five 8-minute (480s) excerpts of the reported data have been selected to realize five realistic time-varying GEF scenarios, as shown in Fig. 8; the magnitude has been multiplied by four to scale the data to 5V/km level, and the angle has been changed to 45º which is the worst case for this particular network [15]. Fig. 9 shows the simulation results of peak number 5 in Fig. 8. As shown, the network collapses at around 160s.

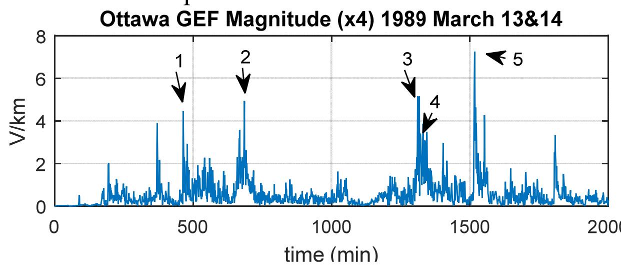


Fig. 8. Time-varying GEF waveform of the five scenarios of Section VI. A.

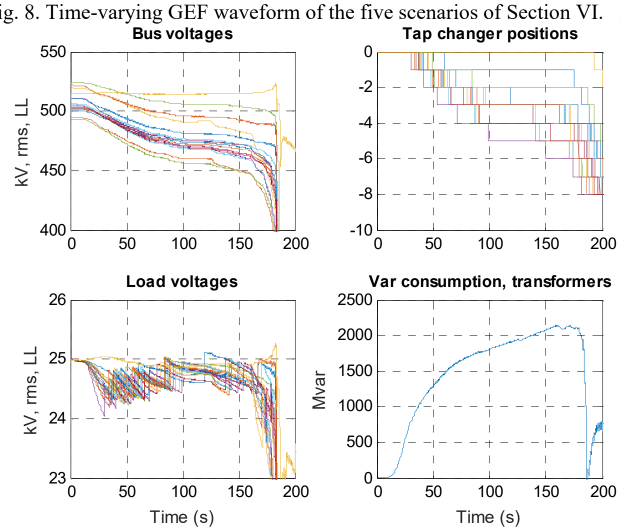


Fig. 9. Simulation of voltage collapse of case 5, Section VII. A.

The CPU computation time of the simulation test of Section VII. which includes detailed generator models, OELs, OLTCs, saturation, and hundreds of periodic meters is significant yet acceptable considering the high level of precision obtained in this GMD simulation. For a numerical integration time-step of 80µs and a simulation duration of 200s, the CPU time was about 4 hours on a 2.6 GHz processor.

VIII. Conclusions

This paper has proposed an EMT-type benchmark, based on a modified version of IEEE-39, for the simulation of a GMD in a power system. The paper has studied the impact of a GMD on the response of protection of shunt capacitor banks due to excessive harmonics; such a study is essential since reactive power devices provide crucial voltage support during a GMD. The paper has further studied the response of distribution transformers to a GMD. A voltage collapse case study with realistic time-varying GEF waveforms was presented. The paper has demonstrated that EMT-type simulation methods can be advantageously used to study GMD impacts on power systems with accurate/detailed models and for very long simulation intervals.

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