Letters

Converter-Based Power System Protection Against DC in Transmission and Distribution Networks

Moazzam Nazir, Klaehn Burkes, and Johan H. R. Enslin

***Abstract*—The dc in a power system may be caused by geomagnetic disturbances that are the result of solar storms and high-altitude nuclear detonations. Increased inverter-based generation is also contributing to small dc injection into the power systems. The resultant dc could have serious consequences for the power systems as it may drive power transformers into saturation, cause transformer internal heating, cause large draw of reactive power, and misoperation of protective relays. This letter proposes a novel power electronics-based dc mitigation approach that involves a transformerless series active filter integrated between the neutral point and ground of power transformers serving multiple purposes. The first objective is to surpass the effect of dc injection, the second goal is voltage regulation, and the third is to provide harmonic isolation or impedance balancing. The proposed device is currently being developed on a 7.2-kV/240-V single-phase transformer; however, the solution is also relevant for 24–500-kV networks. The system circuitry, operation, and control are implemented and verified for this letter in a controller hardware-in-the-loop (C-HIL) test setup using a Typhoon HIL-402 simulator. Results indicate that our approach is a promising alternative to traditional neutral capacitor-blocking strategies.**

***Index Terms*—Active filters, geomagnetic disturbance, harmonic isolation, power quality, transformer protection.**

I. Introduction

GEOMAGNETIC disturbances (GMDs) are the result of coronal mass ejection (CME). The CME refers to the ejection of large mass of charged solar energetic particles from the sun's halo [1]. This phenomenon is depicted in Fig. 1. The charged particles travel toward the earth and as they reach near the surface, they distort the earth's magnetic field leading to large amount of electric currents, travelling around the E-region of the ionosphere, known as electrojets [3]. These currents induce voltages in the transmission lines and further lead to the flow of currents, through the ground as well as transmission lines, known as geomagnetically induced currents (GICs) [4], [5]. The mutual coupling process leading to the flow of GICs in a power system is shown in Fig. 2. GICs are quasi-dc in the frequency range of 0.1 mHz to 0.1 Hz. Transformer neutral currents of up to 200 A with time duration of 100–1000 s have been reported in the auroral regions in the United States and Canada [3]. The strength and duration of the GICs can saturate the transformers core, cause internal heating, cause large draw of reactive power, can cause misoperation of protective relays, etc. [6].

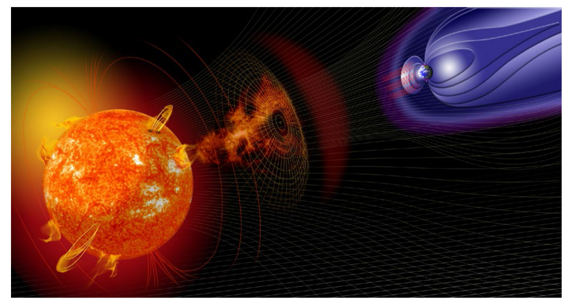

Fig. 1. CME [2].

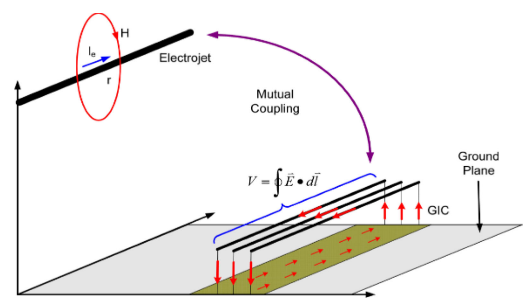

Fig. 2. Currents flowing in space magnetically coupled with the transmission lines [3], [4].

A similar phenomenon is caused by the nuclear detonation at a height of 30 km or more above the earth's surface, commonly referred as a high-altitude nuclear electromagnetic pulse (HEMP). The detonation spreads the gamma particles in a wide area. Their collisions with air molecules lead to the ionization of atmospheric layer and generate an electromagnetic signal that

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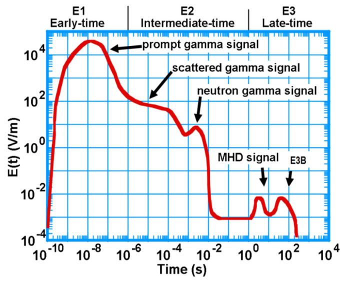

Fig. 3. Various phases of an HEMP [7].

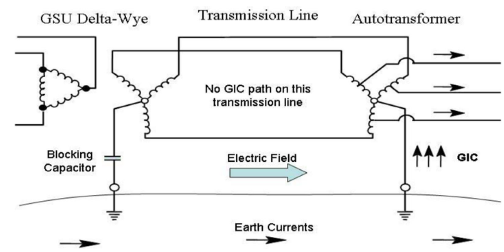

Fig. 4. Neutral capacitor-blocking scheme [10].

might interact with the transmission lines. The nuclear electromagnetic pulse burst can be divided into three-time regions: E1, E2, and E3. The E1 is an early-time wave with magnitudes ranging in the order of 10^4 V/m and with 50 ns of duration. On the other hand, E2 is an intermediate-time wave with a duration of about 1 s. The last wave portion is the late-time magnetohydrodynamic (MHD-E3) component that has a duration of about 300 s and resembles a solar storm. The various types of HEMP pulses are shown in Fig. 3.

Apart from CME and HEMP MHD-E3 GIC, inverter-based generation is also injecting small dc into the power networks. Although some strategies have been proposed to avoid this dc injection, as in [8], there are still cases where the inverters might not be equipped with these controls or do not mitigate dc injection altogether and where dc needs to be mitigated on a system level.

The grid reliability against GMDs is highly critical for North America due to the increased frequency and severity of GMDs in recent years. In 1989, the severe geomagnetic storm on the Hydro Quebec System led to the collapse of the system, where 6 million people were left without power for 9 h. The estimated equipment damage cost was $13.2 million [6]. Due to the criticality of high-voltage systems in bulk power transfer, the elimination of dc becomes of prime importance [9]. Different dc elimination strategies have been proposed in past [10]–[16]. These include elimination of neutral connections, series compensation, or neutral capacitor blockers. The elimination of neutral connections is not recommended from the safety and system protection point of view. Also, single-phase autotransformers are highly utilized and always require the neutral grounding to avoid over voltages. The series compensation may cause series and parallel resonance from line and load impedances, thus, affecting the system stability and it removes dc to a mere 12–22% [1]. Moreover, they need to be installed along the length of transmission lines and are, therefore, highly expensive. The most widely utilized technique is installation of neutral capacitor blockers between the transformers neutral and ground, as shown in Fig. 4.

The installation of neutral dc capacitor blockers brings significant uncertainty and risk due to transformer impedance changes and ferro resonances. As the increasing inverter-based generation is also constantly injecting dc into the power networks, in addition to the GICs, any device that constantly eliminates dc without affecting other power system equipment is highly desired. All current technologies utilized for GIC mitigation or elimination remain dormant when there is no flow of these quasi-dc in a power system. Therefore, they remain unutilized most of the time due to low occurrence of such events.

In this letter, the aim is to surpass the effect of dc while performing certain grid-support functions such as harmonic isolation, voltage regulation, and impedance balancing [17]–[19]. Active power filtering (APF) has been widely used for power quality improvement, harmonic isolation [20], and voltage regulation [21]. Transformerless series active filters have been specifically utilized for voltage sag compensation in [17]. A power electronic converter is also utilized for certain grid-support functions on the tertiary low-voltage winding of a three-winding transformer in [19]. The implementation of this approach specifically requires a special tertiary winding transformer and may not be applicable to existing networks. The proposed approach in this letter can be implemented on existing two winding or autotransformers without the need of a tertiary winding, thus, allowing incorporation to existing power networks. In the proposed approach, power electronics is utilized on one side of the utility transformers to actively isolate voltage harmonics at the point of common coupling (V_{PCC}) and regulating the load voltage at the same time. A series transformerless compensator is designed and implemented that subtracts the harmonic components from V_{PCC} to cancel out their unwanted effects as well as it monitors and regulates the load voltage. In this way, the proposed APF approach provides transformerless harmonic isolation, voltage regulation while detects and eliminates dc. The proposed approach is currently being verified on a single-phase 7.2-kV/240-V distribution transformer, but it is scalable toward the 24–500-kV networks.

II. Proposed DC Mitigation and Grid-Support Strategy

In this letter, a transformerless power electronics-based alternative solution is proposed for the mitigation of the unwanted effects of dc on transformer saturation along with certain grid-support functions. A single-phase version of the proposed scheme is presented in Fig. 5, where a series active filter with an H bridge is integrated between the neutral and ground of a power transformer. The capacitor C_1 and inductor L_1 act as a high-frequency filter for the converter. During the flow of dc, the amount of power that is injected to the transmission line can be drawn from dc capacitor C_2 and/or dc link connected across dc side of the H-bridge. In event of inrush current or ground fault, the switch parallel to capacitor C_1 is closed using a signal from an overvoltage (OV) relay followed by the converter operation in the current-controlled mode to avoid its damage.

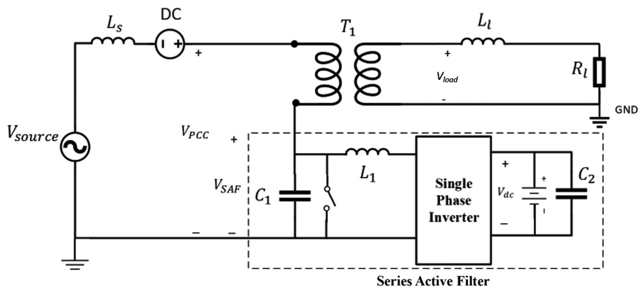

Fig. 5. Proposed circuitry for dc elimination and grid support.

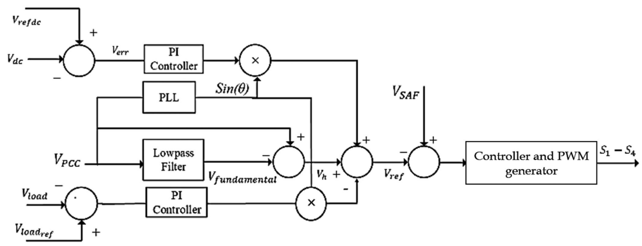

Fig. 6. Proposed controller for the series power filter.

The controller proposed for the series active filter is demonstrated in Fig. 6. The designated controller regulates the dc side of the inverter V_{dc}, regulates the load voltage, and eliminates the harmonics from the V_{PCC}. For the first two regulation purposes, the respective actual values are compared with references and further passed through PI controllers. The resultant control amplitudes are multiplied by the sine of the phase angle of V_{PCC} to bring them in phase harmony with the V_{PCC}. The harmonics in the V_{PCC} are obtained using a low-pass filter, with a time delay of 1.08 ms, to extract the fundamental and then subtracting it from the actual value. All the three control signals are added, and the sum is compared with the actual filter voltage V_{SAF}. The error signal is further passed through a controller to get the final control signal. A pulsewidth modulation generator generates pulses for the single-phase converter. The PI controllers utilized in the control structure are tuned with a trial-and-error procedure.

After presenting the proposed scheme for dc mitigation and grid support, the concept and control approach are evaluated and verified with a Typhoon hardware-in-the-loop (HIL) 402 real-time simulator. The HIL-402 unit consists of four cores, 16 analog input, 16 analog output, 32 digital input, and 32 digital output channels. The HIL control center is utilized to build the power stage that simulates in real time within the HIL unit. The unit provides the interface board for the third party controllers to simulate the control stage. The overall test setup is shown in Fig. 7. The setup is utilized to test and verify the real time performance of the Texas Instrument controller TMS320f28335 with the designed power stage in the Typhoon software. The next section presents the controller HIL (C-HIL) simulation results and its associated discussion.

III. C-HIL Results and Discussion

In order to explore the performance of the proposed scheme, it has been implemented in Typhoon HIL-402 real-time simulator and the associated results are presented. The circuit elements

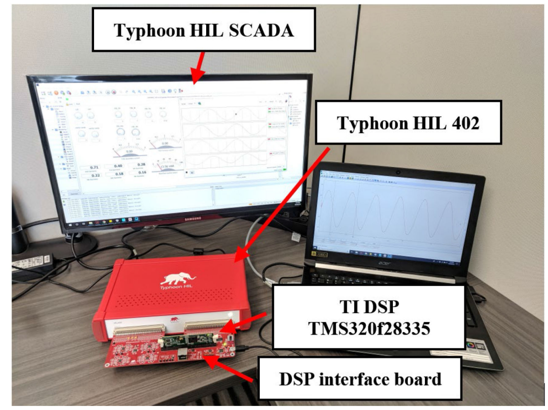

Fig. 7. C-HIL setup to verify the proposed approach.

TABLE I
System Parameters for Test Case

Circuit Component		Component value
C_1		100uF
C_2		2.3mF
L_1		3mH
L_s		1mH
L_l		1mH
R_l		3Ω
V_{dc}		1000V
Transformer	$V_{primary}$	7.2kV
	$V_{secondary}$	240V
	kVA	25

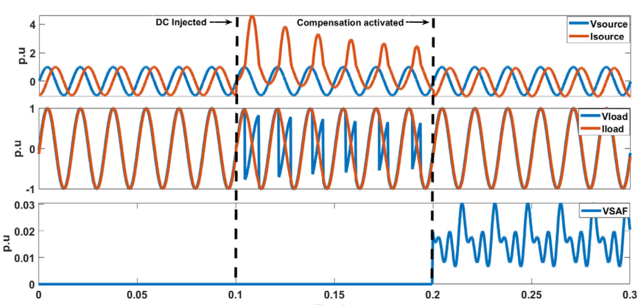

Fig. 8. Proposed filter performance under dc.

and the transformer parameters utilized for the current study are presented in Table I. First, the source and load voltages and current signals of the transformer under normal operation without dc are recorded. In this case, the total harmonic distortion (THD) of the load voltage is 0%. After that, a dc voltage of 100 V is applied through a series voltage source designed to mimic the effect of dc in power networks. This dc voltage leads to half-cycle saturation of the transformer and increases the THD of the load voltage to 29%. The high value of the source current after dc application settles down to 2 p.u. in about 200 ms and stays there as long as the dc is applied. The proposed filter is later applied between the neutral and ground of the transformer and the resultant waveforms are presented in Fig. 8, where V_{SAF} is the injected filter voltage.

It can be observed that the source and load voltages and currents are recovered back to their sinusoidal characteristic, as before the injected dc, after the mitigation with the proposed

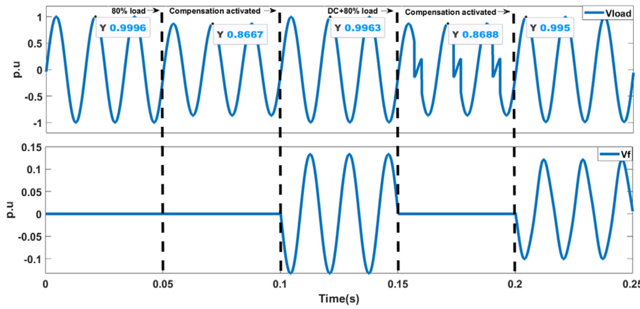

Fig. 9. Proposed filter performance under dc and 80% load voltage.

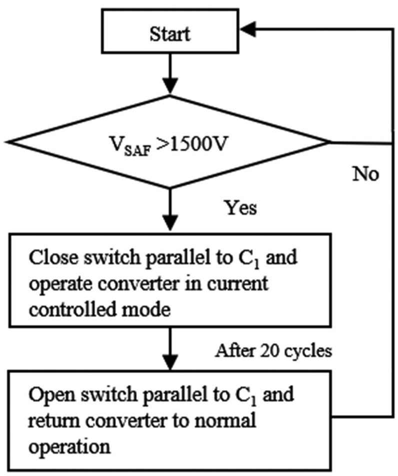

Fig. 10. Flowchart for the converter protection scheme.

power filter. The load voltage THD is also improved to 0.2% after this compensation. We now proceed toward the case that involves both dc and voltage regulation simultaneously. For this case, the load voltage before and after compensation is shown in Fig. 9.

The C-HIL results verify the overall capabilities of the proposed filter to regulate the load voltage in addition to harmonic isolation and dc elimination.

The converter needs to be protected from damaging voltages that might develop at its output terminal during inrush or ground faults. A flowchart showing the sequence of events involved in its associated protection scheme is shown in Fig. 10. The protection scheme involves an OV relay that constantly monitors the voltage on the capacitor C_1 and operates the switch parallel to C_1, as per the algorithm in Fig. 10. The delay of 20 cycles between the last two steps in the flowchart ensures that the inrush currents have already died out or the ground faults have been successfully cleared by the protection devices prior to switching back of the converter.

IV. Conclusion and Future Work

In this letter, a novel transformerless converter-based dc elimination approach has been proposed. The scheme involves a series power filter integrated between the neutral point and earth ground of the utility transformer. The filter simultaneously addresses the harmonic isolation, surpasses the effect of dc, and fulfills the voltage regulation requirements. The system is implemented and verified in Typhoon HIL-402 real-time simulator. The simulation results indicate the promising performance of the framework as an alternative to traditional capacitor-blocking strategies. The future work involves the development of a scaled prototype of the proposed mitigation approach and its application on a 7.2-kV single-phase transformer. Also, a detailed economic analysis will be performed that involves finding the optimal placement spots for the proposed device in a transmission and distribution grid.

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