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Analysis of Power Transformer Inrush Current in the Presence of Quasi-Direct Currents

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Abstract— **The flow of quasi-direct currents (QDCs) in AC electrical networks, is a disturbing factor that mainly prevails upon mutual impacts between different system components or due to geophysical phenomena. These QDCs can alter the normal behavior of the system components, e.g., power transformer inrush currents. In this paper, an analysis of the inrush current phenomenon in power transformers under the influence of QDCs has been performed. The effect of QDCs on power transformer inrush currents is first mathematically analyzed, and then investigated by computer simulations in EMTP-RV software. Results show that power transformer inrush currents can severely increase in the presence of QDCs.**

Keywords— half-cycle saturation, inrush currents, quasi direct currents (QDCs), uni-directional flux.

I. INTRODUCTION

In an attempt to answer the growing demand for energy, more electrical power systems are built and interconnected every year. These expansions, however, bring upon new challenges and issues which may impact the power systems unexpectedly. Emergence of electromagnetic interferences (EMIs) due to the presence of unwanted electrical signals is one of the main challenges faced by interconnected power systems. Although it is commonly believed that larger systems are the sources of EMIs affecting smaller systems, depending on the conditions, high voltage (HV) electrical power systems can also become a victim of EMIs. The flow of quasi-direct currents (QDCs) in AC networks is a form of EMIs that can severely impact the continuity of power systems. The QDCs can be driven by various sources such as the space-weather-resultant geomagnetic disturbances (GMDs) [1], monopolar high voltage direct current (HVDC) systems [2], power-electronic-based converters [3], transformer-less photovoltaic (PV) inverters [4], and electrical transportation systems [5].

Considering the tendency of electrical currents to flow through paths with low impedances, and owing to the high susceptibility of an inductive unit against low-frequency components, a grounded power transformer can provide a suitable path for the bilateral flow of QDCs between the electrical network and the ground [6]. The flow of QDCs through a transformer's windings results in the formation of a DC bias in its core flux. The transformer's AC excitation flux adds up to this DC flux in one half-cycle and is subtracted from it in the next [7]. In the condition of severe QDCs, mostly being the case during heavy GMDs, the transformer core is pushed into deep half-cycle saturation, causing numerous harmful effects, e.g., temperature increase [8], harmonic emission [9], reactive power consumption rise [3], voltage instability [10], and ferroresonance [11]. Nevertheless, the impacts of QDCs with relatively lower amplitudes can be less problematic, and thus be more tolerable in the system.

The majority of the research body of QDCs in AC power systems have taken a steady-state approach towards analyzing this phenomenon [12]. Such an attitude, however, lacks in generality, as for being unable to explain the transient and non-linear aspects. As an instance, studies in [11] and [13] showed the impact of GMD-driven geomagnetically induced currents (GICs) on the occurrence of ferroresonance in power systems, highlighting the importance of considering transients of power system components in the presence of QDCs. Transformer inrush current is yet another transient that can be affected by the flow of QDCs in the network.

Upon energization (or re-energization), transformers draw transient currents, referred to as inrush currents [14], [15]. Three types of inrush currents are imaginable including i) magnetizing inrush current provoked by energization, ii) recovery inrush current drawn upon post-trip re-energization, and iii) sympathetic inrush driven by energization or recovery of a nearby transformer [16]. Inrush currents can result in various detrimental impacts including i) potential damage to transformer windings, from thermal and electromechanical stresses due to high currents [17], [18], ii) false operation of protective devices resulting in unwanted trips [19], and iii) power quality problems, e.g., temporary voltage sags [20] and resonance overvoltages due to high harmonic emission [21].

The QDCs can affect inrush currents in two ways: via shifting the drawn inrush currents by biasing the transformer's flux, and via increasing the residual flux which mainly affects recovery inrush incidents. The presence of QDCs in a network can result in the exceedance of the inrush currents over the permissible and/or expected values. Therefore, they are vital to study for the sake of providing adequate mitigation against their adverse effects in transformers prone to such currents.

This paper investigates the behavior of power transformer inrush currents under the influence of QDCs. To such an end, the following contributions are made in this manuscript:

- A benchmark test system is employed to survey the behavior of transformer inrush currents under the influence of QDCs in a more systematic fashion.
- The contribution of different factors involved with the inrush currents subjected to QDCs, e.g., circuit path resistance, and switching angle, are analyzed.

- Based on the results obtained regarding the impacts of involved factors, the applicability of a candidate mitigatory option is investigated.

This research is organized according to the following: In *Section II*, the influence of QDCs on transformer inrush currents is described mathematically, and then verified by a numerical example. In *Section III*, simulations are exploited in favor of a systematic investigation of the paper's main idea, and discussions regarding the results are given. Finally, a concluding summary of this study is provided in *Section IV*.

II. Non-Linear Equivalen Circuit Analysis

Analyzing a simple non-linear equivalent circuit can mark a systematic departure point towards the body of this research, i.e., the impact of QDCs on power transformer inrush currents. In the following, the fundamental principles are first laid out by a mathematical analysis of the simplified equivalent circuit, and then, described numerically by its computer simulation.

A. Mathematical analysis of QDCs' impacts on inrush

The behavior of power transformer inrush currents under the influence of QDCs can be characterized with the help of the simple circuit depicted in Fig. 1a, constituted of the resistor R, and the non-linear inductor L, representing the series resistances of the energizing line together with the transformer winding, and the merged combination of the transformer's magnetizing and leakage inductances, respectively. Since the winding leakage inductance is much smaller than the core magnetizing inductance, it is also neglected in calculations. Accordingly, to avoid redundant complexities, the non-linear inductance L is characterized by a piecewise characteristic shown in Fig. 1b, relating the transformer's instantaneous flux-linkage $\lambda(t)$ to the current $i(t)$ through its windings, as:

$$\lambda(t)=\begin{cases} L_m i(t) & |i(t)|\le i_s \\ L_s i(t)\pm\lambda_1 & |i(t)|>i_s \end{cases} \quad (1)$$

thus, yielding L to be equal to L_m for transformer's operation in the non-saturated region, and L_s for its operation in saturated region with is as the saturation onset current.

In the circuit of Fig. 1a, the excitation voltage is assumed to be sinusoidal with the amplitude of V_{ac}, the angular frequency of ω as $v(t) = V_{ac}\sin(\omega t)$. To maintain the tractability of the study, the voltage phase angle is assumed to be equal to zero. The impact of the QDCs is represented by their driving factor through the series DC voltage source V_{dc}. Therefore, by applying KVL to the circuit in Fig. 1a, the following yields:

$$V_{ac}\sin(\omega t)+V_{dc}u(t)=Ri(t)+\frac{d\lambda(t)}{dt} \quad (2)$$

where $u(t)$ is the unit step function. Replacing the terms for flux-linkage from the relationship (1) in the differential equation (2), and solving for the current $i(t)$, we have:

$$i(t)=K_1\sin(\omega t+\theta)+K_2e^{-t/\tau}+K_3 \quad (3)$$

where θ is the phase angle and τ is the time constant of damping. Relationship (2) is composed of three parts, i.e., a sinusoidal, a decaying exponential, and a constant part. The sinusoidal term corresponds to the steady-state component of

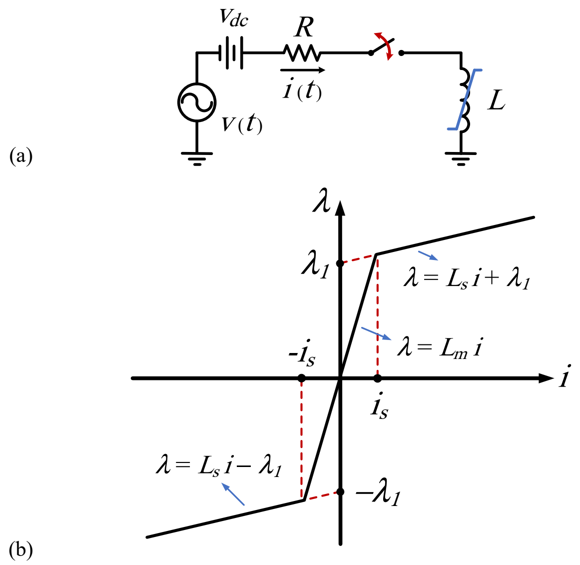

Fig. 1. The basis for mathematical analysis. (a) Non-linear equivalent circuit under study. (b) The assumed magnetization characteristic.

the transformer's magnetization current, and the constant term K_3 is obtained to be equal to V_{dc}/R, indicating the steady-state component of the QDCs flown through the transformer. On the other hand, the transient behavior of inrush current is described by the decaying exponential term as:

$$K_2=\frac{\tau^2\omega}{L\left(1+(\tau\omega)^2\right)}V_{ac}-\frac{1}{R}V_{dc}+\frac{1}{L}\lambda_0 \quad (4)$$

where λ_0 is the remanent flux. The maximum value of the inrush current's transient component, i.e., the decaying exponential term, occurs at the switch-on instant (t=0+), and is accordingly determined by K_2 given in (4), demonstrating two important points. First, considering that $L_s \ll L_m$, the value of K_2 is increased in the saturation region, which shows that inrush currents are increased under half-cycle saturation conditions in the presence of QDCs. Second, the term $-V_{dc}/R$ is canceled by the DC component of the magnetizing current $K_3=V_{dc}/R$ at the switch-on instant, and as time passes, the transient exponential component is died out, leaving behind the DC component in the steady-state.

According to the above analysis, one can argue that the energization inrush currents are only affected by the steady-state component of the QDCs in the long term. Nevertheless, the presence of stray DC currents can also impact the inrush currents alternatively via the remanent flux. This condition, being mostly the case for the recovery inrush currents, occurs when a transformer with high values of magnetic flux from the half-cycle saturation of its core in the presence of QDCs is interrupted and then re-energized. Such a relatively high magnetic flux remained in the transformer core can highly increase the drawn inrush current upon its re-energization. Also, with the term λ_0/L, representing the effect of remanent flux, and noting that $L=L_s$ with respect to the transformer's saturated operation during these conditions, even severer recovery inrushes can be expected in the presence of QDCs.

The presented mathematical analysis, although being based on simplifying assumptions, can also provide a good intuition about the fundamental concepts of this study, e.g., the cancelation of the DC component at the switch-on instant,

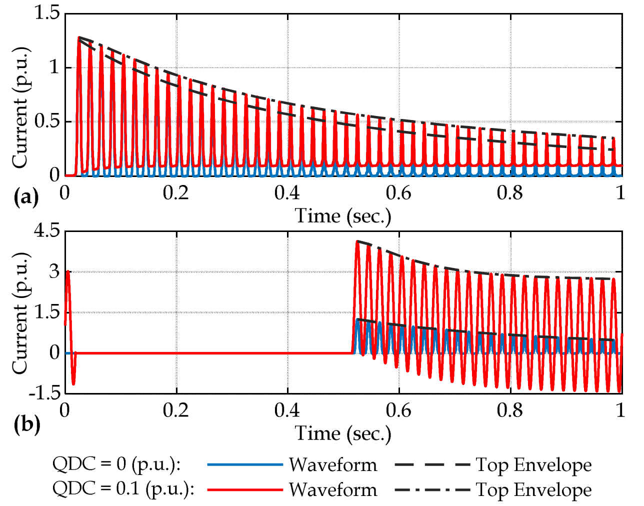

Fig. 2. Inrush current waveforms of the simple circuit under study. (a) Energization inrush currents. (b) Recovery inrush currents.

TABLE I. FLUX-CURRENT CHARACTERISTIC

Magnetizing Current (p.u.)	0.002	0.01	0.025	0.05	0.1	2
Flux-Linkage (p.u.)	1	1.075	1.15	1.2	1.23	1.72

the increased severity of the recovery inrush currents, and the dependency of the damping time constant of the inrush currents to the system's reactance to resistance characteristic.

B. Numerical analysis of inrush under QDCs

The authenticity of the conducted mathematical analysis can be verified by an EMTP-RV simulation of the studied simple circuit in Fig. 1a, with V_{ac}=1 per-unit (p.u.), ω=2π×50 rad/sec., R=0.003375 p.u., and a flux-current characteristic according to Table I for the non-linear inductor. In this test, both the energization and recovery inrush current phenomena have been studied in two conditions with QDC being equal to 0 and 0.1 p.u. For the energization inrush, the normally-open switch is closed to connect the non-linear inductor at 15 ms, while for the recovery inrush, the normally-closed switch is opened at 15 ms, and then reclosed at 515 ms, re-energizing the non-linear inductor after a dead-time of 500 ms. It is to note that the initial condition of the inductor is considered zero at the beginning of all simulated cases. Fig. 2 demonstrates the behavior of the circuit's inrush currents in response to the described operations under both 0 and 0.1 p.u. QDC.

The waveforms illustrated in Fig. 2 are in clear agreement with the results of the mathematical analysis carried out in the previous sub-section. As shown in Fig. 2a, since the inrush current waveforms are first identical at the switch-on instant but then diverge exponentially, it is confirmed that the DC component of the inrush current is canceled at the switch-on instant, and then rises up to its steady-state value. Moreover, Fig. 2b shows that the severity of recovery inrush current is significantly increased in the presence of QDCs.

The mathematical analysis above, and the numerical verification of the arguments entailed with it, establish a basis for the foundations of this study. In the following, the effects of QDCs on the behavior of inrush currents are investigated in detail, characterizing the influence of involved parameters.

III. Computer Simulation and Discussion

In this section, an investigation is put forward based on a simulation model to study how the QDCs affect the domestic

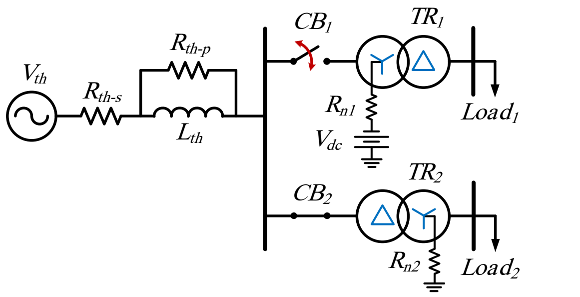

Fig. 3. Simulated system for analyzing QDCs' impact on inrush currents.

TABLE II. SPECIFICATIONS OF THE TEST SYSTEM

Parameter	V_{th}	R_{th-s}	R_{th-p}	L_{th}	R_{n1}	R_{n2}
Value	420 (kV)	0.8 (Ω)	3000 (Ω)	30 (mH)	2.5 (Ω)	2.5 (Ω)

and sympathetic inrush currents, drawn by the power transformers upon energization and re-energization. With the help of the results obtained from this investigation, the effects of involved factors are determined, and applicable options to mitigate the adversities that emerged due to the influence of QDCs on inrush currents are analyzed.

The adopted test system for this analysis, as shown in Fig. 3, is constituted of two 400 MVA, 420/245 kV three-phase banks of single-phase transformers with winding connections according to the figure, and supplied from a 420 kV power system, modeled by its Thevenin equivalent. A per-unit magnetizing characteristic according to Table I is considered for both the transformers, and resistors R_{n1} and R_{n2} are added to their star point ground connections. Moreover, the QDCs are modeled by the DC voltage source V_{dc}, positioned at the neutral of the transformer TR_1. The specifications of the test system under study are given in Table II. The EMTP-RV software has been used for the simulation of the test system.

In the adopted test system, it is assumed that the breaker CB_2 is normally closed and the transformer TR_2 operates in the

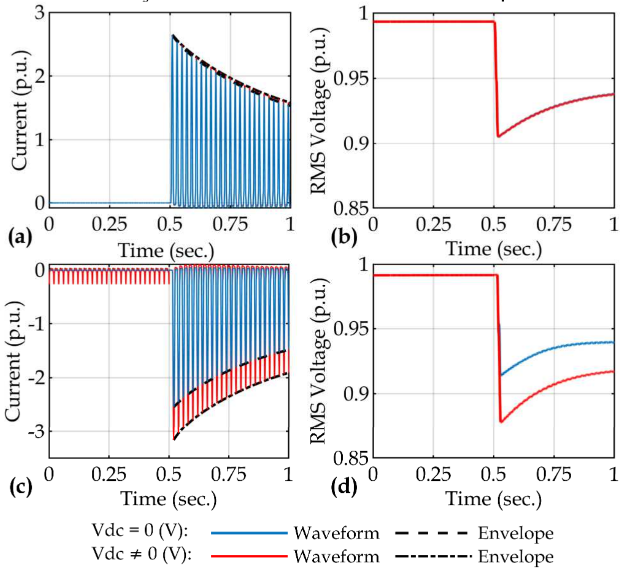

Fig. 4. Impact of QDCs on domestic and sympathetic inrush phenomena during energization and re-energization. (a) Inrush currents in the primary of TR_1 upon energization. (b) Voltage sags at the secondary of TR_2 upon energization. (c) Inrush currents in the primary of TR_1 upon re-energization. (d) Voltage sags at the secondary of TR_2 upon re-energization.

normal condition. By properly setting the closed/open states of the breaker CB_1, energization and recovery inrush current conditions are simulated. It is noteworthy that as the transformer TR_1 draws domestic inrush currents, sympathetic inrush currents also prevail in transformer TR_2 accordingly. Fig. 4 demonstrates the effect of QDCs on energization and recovery inrush phenomena in the test system. The adverse impact of QDCs on sympathetic inrush phenomena experienced in an adjacent transformer has been characterized by the voltage sag in the secondary of the normally connected transformer TR_2. As expected, Figs. 4a and 4b verify that the QDCs do not notably impact energization inrush phenomena, and on the other hand, the impact of QDCs on recovery inrush phenomena is distinctively confirmed by Figs. 4c and 4d.

In the following, the test system is used to analyze effects of ground resistance and switching angle as two influential parameters on power transformer inrush currents. To such an aim, the maximum peak inrush current in the primary of TR_1 and the maximum voltage sag in the secondary of TR_2 have been adopted as the criteria to characterize the effects of domestic and sympathetic inrush phenomena, respectively.

A. Effect of Ground Resistance

The ohmic resistance of the circuit is an influential factor for both the inrush current and QDC phenomena. Increasing the power flow path resistance will result in excessive system loss. On this account, pre-insertion resistors and neutral resistors are popularly used for limiting the flow of QDCs and inrush currents in practice [11], [22]-[23]. The effect of circuit path resistance, as a potential strategy for mitigating the adversities of inrush currents in the presence of QDCs, can be studied with the help of the grounding resistance R_{n1} in the test system. Numerous inrush occurrences considering three resistance values of 2.5 Ω, 25 Ω, and 250 Ω for the grounding resistor R_{n1} have been simulated in the test system based on different closing angles for energization and different opening and re-closing angles for recovery. The simulation results for energization and recovery inrush occurrences have been respectively shown in Figs. 5 and 6, where each dot

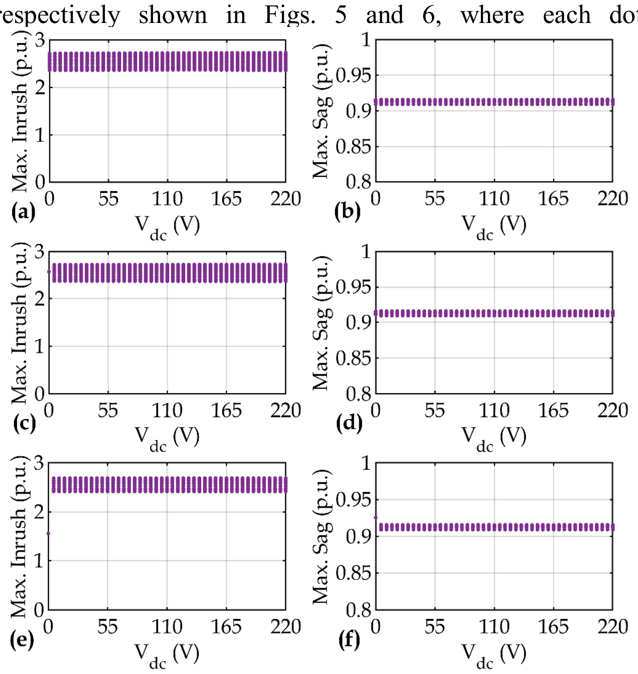

Fig. 5. Effect of ground resistance on energizarion inrush. Left side: Inrush currents in the primary of TR_1. Right side: Voltage sags at the secondary of TR_2. (a) and (b) R_{n1}=2.5Ω, (c) and (d) R_{n1}=25Ω, (e) and (f) R_{n1}=250Ω.

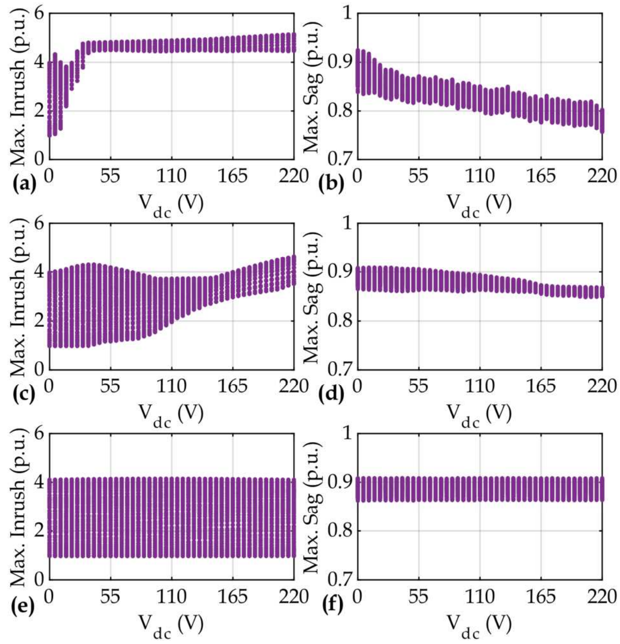

Fig. 6. Effect of ground resistance on recovery inrush. Left side: Inrush currents in the primary of TR_1. Right side: Voltage sags at the secondary of TR_2. (a) and (b) R_{n1}=2.5Ω, (c) and (d) R_{n1}=25Ω, (e) and (f) R_{n1}=250Ω.

corresponds to a single simulation of the test system. As noted previously, the effect of domestic inrush has been represented by the maximum inrush current experienced at the primary side of the transformer TR_1, while the effect of sympathetic inrush has been represented by the maximum voltage sag experienced at the secondary side of the transformer TR_2.

As the weak dependency of energization inrushes and strong dependency of recovery inrushes to QDCs are verified, Figs. 5 and 6 show that increasing the grounding resistance does not notably affect energization inrushes, whereas this practice can very well restrain recovery inrushes under QDCs.

B. Effect of Switching Angle

Another popular strategy for restraining the impacts of inrush currents is the controlled switching [24]. This method takes advantage of the inrush currents' dependency on the point-on-wave at which the transformer is energized, by controlling the closing angle of the transformer's supplying circuit breaker. In order to analyze the impact of switching angle on the domestic and sympathetic inrushes upon energization and re-energization in the presence of QDCs, the grounding resistance R_{n1} is held constant equal to 2.5 Ω, and the switching-on instant of the circuit breaker CB_1 is varied over one full-cycle. It is to mention that in the case of recovery inrush, the reclosing angle has been considered as the variable. The analysis has been carried out considering three different values of 0, 110, and 220 V for V_{dc}. Figs. 7 and 8 illustrate the variation of maximum inrush currents in phase-a of the transformer TR_1 primary based on variation of switching angle over one cycle for energization and recovery, respectively.

As can be seen in Fig. 7, the energization inrush currents, although depending on the energization angle, do not represent a notable dependency on the level of QDCs. On the other hand, Fig. 8 demonstrates that recovery inrush currents exhibit a rise in response to the increase of QDCs. The most notable result characterized in Figs. 7 and 8 is that the maximum amplitude of energization and recovery inrushes for phase-a are well suppressed around the switching angles π/2 and 3π/2. It is deduced that by controlling the per-phase point-

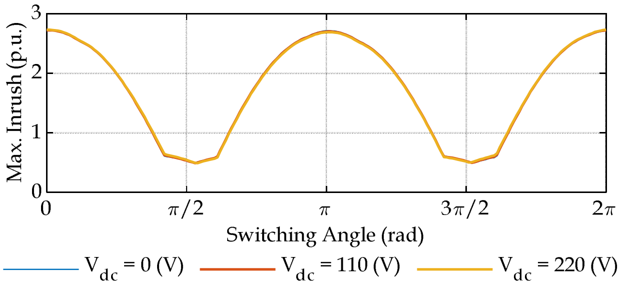

Fig. 7. Effect of swithing angle on energization inrush phenomena.

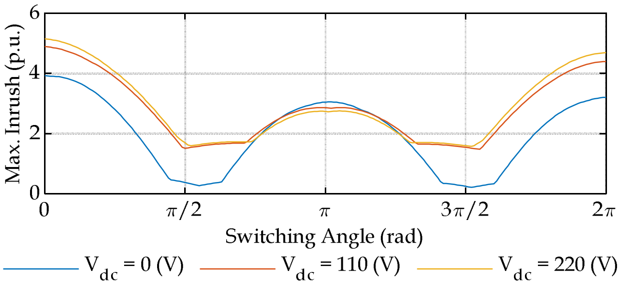

Fig. 8. Effect of swithing angle on recovery inrush phenomena.

on-wave energization angles of the transformer adversities of inrush currents, even in the presence of QDCs is possible.

C. Proposed Mitigation Strategy

According to the results obtained in the previous two sub-sections, a mitigation strategy can be proposed for limiting the adverse effects that arose from the impacts QDCs may impose on transformer inrush currents. In this technique, as shown in Fig. 9, a controller is implemented to manage the transformer energization by i) inserting a neutral resistance and ii) controlling the switching angles of each phase with the objective of minimizing the inrush currents. It is to note that the resistance is only inserted during the energization period, and is then bypassed due to protection considerations [25].

As can be seen in Fig. 9, the proposed mitigation scheme is implemented on transformer TR_1 of the test system. In order to preserve simplicity, R_{n1} isconsidered equal to 250 Ω, and the phase switching angles are set to π/2 with respect to their corresponding phase voltage. Similar to the previous sub-sections, the V_{dc} source is applied to characterize the effects of QDCs. The results demonstrated in Figs. 10 a and b correspondingly show the maximum inrush current flown in the primary side of TR_1 and the maximum voltage sag in the secondary side of TR_2 for energization and recovery inrushes. The effectivity of the proposed scheme is confirmed by the results in Fig. 10 where the maximum drawn inrush currents and the resultant maximum voltage sags upon energization and recovery are well limited for different levels of V_{dc}.

D. Discussion

For the sake of a detailed analysis on the influence of QDCs on transformer inrush phenomena, an example power system simulated in EMTP-RV software was adopted as the study test-bed. Primarily, the consistency of the test system's inrush behavior with the mathematical and numerical analyses in the previous sections was confirmed. The maximum current drawn by transformer TR_1 of the system in its primary side and the maximum voltage sag experienced in the secondary side of an adjacent transformer TR_2 were taken as the criteria to characterize domestic and sympathetic impacts of transformer inrush phenomena, respectively. First, to study the effect of ohmic resistance of the circuit path on the behavior of the test system's domestic and sympathetic inrush phenomena upon

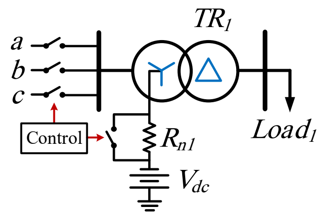

Fig. 9. Proposed scheme based on controlled switching for phase energization and neutral resistance insertion.

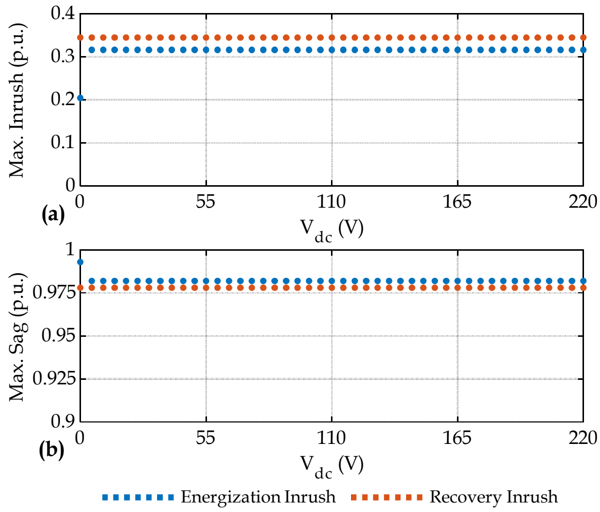

Fig. 10. Effect of proposed mitigation strategy on energization and recovery under QDCs: (a) on maximum drawn currents in the primary of TR_1, (b) on maximum voltage sag experienced in the secondary of TR_2.

energization and recovery, the test system was simulated considering different neutral resistance values including 2.5 Ω, 25 Ω, and 250 Ω for various switching-on angles within a full-cycle. By increasing V_{dc} as the driving source of QDCs, it was observed that while energization inrush phenomena are not significantly affected by QDCs and the employment of a neutral resistor, recovery inrushes are highly dependent on the QDC level and their adversities can be well mitigated by increasing the transformer's neutral resistance. Afterward, by holding the neutral resistance on the minimum, i.e., 2.5 Ω, and taking the switching-on instant as the variable, the effect of transformer energization (or re-energization) angle was studied. As expected, it was observed that the energization inrush currents are barely affected by the QDCs. Nevertheless, the inrush currents were found to be minimum in certain switching angles, i.e., around π/2 and 3π/2 with respect to their corresponding voltage phase angle. On the other hand, as the dependency of recovery inrush currents to QDCs was again verified, same results were observed regarding inrush currents being in their minima at switching angles around π/2 and 3π/2 with respect to their corresponding voltage phase angles. Further on, using the results obtained for the effects of neutral resistance and switching angle on the drawn inrush currents in under QDCs, a controlled switching strategy was proposed to restrain their resultant adversities. In this technique, first, a 250 Ω resistor is inserted in the neutral of the transformer TR_1 upon energization (and re-energization) and is bypassed afterward. Also, switch-on angles of transformer phases are controlled for attaining the lowest inrush currents. For simplicity, the switch-on angles were set π/2 with respect to each phase's reference voltage angle. The results obtained from this technique demonstrate its effectiveness in alleviating the energization and recovery inrushes and mitigating the resultant voltage sags on adjacent transformers, even in the presence of different amounts of QDCs.

IV. Conclusion

The presence of QDCs in AC power systems can interfere in the magnetization of transformer cores and subsequently disrupt the normal behavior of their inrush currents. Even small amounts of QDCs can have a severe impact on the inrush currents. As discussed, various factors are involved in the flow of QDCs including GMDs and the proximity of power electronic devices and monopolar HVDC links. In this paper, the effects of QDCs on power transformer energization and re-energization were thoroughly assessed. To this end, a mathematical basis was first developed to obtain a reliable perspective towards the general frameworks of this study. The mathematical analysis, executed on a simplified circuit model of the phenomena under study, demonstrated that i) in the presence of QDCs, the DC component of the inrush currents are initially rejected at the switching-on instant and is then gradually increased to its steady-state value; ii) dissimilar to energization inrush currents, QDCs can lead to severe increase of recovery inrush currents. Afterward, the authenticity of the results obtained from the mathematical analysis was also highlighted by numerical simulation of the very circuit which was analytically studied in EMTP-RV. The agreement of the mathematical and numerical analyses confirms the main idea of this paper, i.e., the influence of QDCs on power transformer inrush current. Hereafter, an example power system was adopted and simulated in EMTP-RV as the study basis for investigating the impacts of QDCs on transformer inrush phenomena and their involved parameters on the real scale. The current in the energized (or re-energized) transformer's primary side and the voltage sag experienced in an adjacent transformer's secondary side were chosen as the criteria to characterize the domestic and sympathetic impacts of inrush phenomena, respectively. In the test system, results from the mathematical and numerical studies regarding the respective weak and strong effect of QDCs on energization and recovery inrush currents were reconfirmed once more. In addition, it was demonstrated that by utilizing grounding resistors and accordingly increasing the circuit path resistance, the adverse effects of the inrush currents under the influence of QDCs can be reduced. On the other hand, by analyzing the dependency of inrush currents on the transformer switch-on instant, it was specified that the effects of inrush currents are minimum at certain switching angles. Based on the results regarding the effects of the neutral resistor and switching-on angle on the inrush currents in the presence of QDCs, a mitigation strategy was developed and tested on the system under study. The studies show the effectiveness of the proposed mitigation technique for restraining the adverse impacts of inrush currents imposed due to the presence of QDCs.

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