Transformer Inrush Current Moderation Through Series Voltage Compensation

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Abstract: Voltage sag is 92% of industrial power system installations, leading to reduced system efficiency and significant commercial and economic losses for manufacturers. Voltage sag compensators, which generally include transformer-coupled voltage-source inverters, are successful solutions against such sags. Transformers installed at critical load provide electrical isolation but are subjected to abnormal voltages & DC flux voltages offset during voltage sag. When the compensators replace the load voltage, the transformer's flux linkages can contact magnetic saturation, resulting in severe inrush currents. These inrush currents have the potential to trigger the compensator's overcurrent protection, interrupt the compensation process, and lead to load disruption. This paper proposes a voltage sag–based mitigation strategy to reduce transformer inrush current, compensators, ensuring reliable compensation and uninterrupted power supply to critical loads.

Keywords: *Magnetic Flux Linkage, Starting Current Surge, Electrical Transformer, Potential Drop Using a Voltage Sag Compensator.*

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I. INTRODUCTION

Recent technological advancements have significantly increased system load demand advancement. Power quality issues have become more prominent as fluctuating load conditions affects the system. Voltage sag results from a quick rise in the distribution system's current brought on by an abrupt load surge, which also creates a matching voltage decrease down the line.

➢ *Three Adverse Consequences are Present. Currents of Inrush:*

- Transformer may be disconnected if protective measures for overload and internal faults are misoperated.
- Mechanical pressures have an impact on the windings and harm the transformer.
- The Power quality problem also arises &, voltages sag.

A variety of techniques for mitigating inrush have been developed, actively regulating the transformer current or regulating the power-on angle and voltage magnitude. The techniques will change the converter's output voltage waveforms; hence, they are not suitable for voltage sag compensators. The voltage sag occurs when the fundamental voltage's root mean square value suddenly drops to 0.1–0.9 per unit and maintains the cycle between 0.5 and 30. The load transformer changes to incorrect voltages before the development of the restoration and magnetic flux variation within the transformers with loads. There exists a large inrush current whenever the core is saturated. The compensation fails, and then the compensators own overcurrent protection kicks in and the voltage sag cuts off the load. An inrush mitigation system are explained in this work. This control can lower the load on transformers inrush current.

II. LITERATURE SURVEY

Based on the theory review, voltage sag is a serious issue with power systems. Numerous inrush mitigation strategies were proposed by different scholars involving & effectively Regulating transformer current [6-8] or managing power concerning angle and voltage magnitude [1-5] To achieve effective load voltage restoration during sag events, the voltage sag compensator must accurately regulate the point-on-wave and adjust the converter output voltage waveform accordingly, these techniques are useless. Poor generation and load shedding affect distribution transformers to flip frequently. About 10 times the full load is the transient inrush current.

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➢ *Three Methods to Mitigate Inrush Currents in Distributed Lines and Transformers:*

- The timing of energization strongly affects the magnitude and nature of transformer inrush current.
- Capacitive compensation applied to an unloaded transformer section represents another inrush current mitigation technique.
- The distribution line can also function as a low-pass filter to suppress high-frequency inrush-related transients.

These plans are beneficial for traction transformers and poorly supplied and maintained distribution lines, especially traction lines that undergo continuous changes [1] A novel, straightforward, and cost-effective method for mitigating inrush currents produced during transformer energisation. A grounding resistor is employed at the neutral point of a transformer. The neutral resistor functions as a series-inserted resistance within the circuit, sequentially energising the transformer's phases and significantly reducing the inrush currents during energisation. A single resistor is introduced, and it maintains a neutral current in steady-state; the proposed solution is cost-effective. [2]. Successive phase energisation reduces inrush current. The plan activates each transformer by linking a resistor to its neutral point. In the sequential energization of a transformer, the resulting inrush current is highly dependent on the voltage level across the circuit breaker at the instant of its closure. This study indicates that the concept of sequential phase energisation leads to various techniques for minimising switching transients [3]. The temporary over fluxing in The magnetizing inrush current generated during transformer energization is a consequence of core nonlinearity, and switching parameters like the primary winding resistance, the voltage waveform angle at the moment of energization, and the residual magnetic flux inside the core largely determine its magnitude. [4]. A technique that eliminates the need to rate the series input transformers for the DVR temporary switch-on period is proposed by the authors in [5]. This reduces the redundancy that is frequently associated with their continuous functioning. When a voltage sag begins, transient operating conditions can cause the flux linkage in the DVR to increase substantially, reaching multiple times its steady-state magnitude due to sudden changes in injected voltage. This work presents the method for reducing transformer inrush current [8]. A transformer was connected in series with a rated voltage PWM converter through an appropriate transformer.

III. SYSTEM EXPLANATION

As illustrated in Fig. 1, a three-phase voltage-source inverter (VSI) and a coupling transformer connected in series make up the voltage sag compensator. Thyristors by pass compensator under normal grid conditions to enhance operational efficiency. During voltage sag, the compensator injects the required voltage through the coupling transformer, ensuring that critical loads maintain a stable voltage. For effective sag detection, the compensator controller requires a predetermined detection interval of 4.0 ms [19]–[21] During the sag event, the load transformer experiences distorted voltage until the compensator restores the load voltage. Rapid restoration may lead to magnetic saturation in the transformer, resulting in a high inrush current. This inrush can potentially trigger the compensator's overcurrent protection, causing a temporary loss of compensation. In order to mitigate this issue, the current study suggests modifying the load transformer's flux linkage offsets.

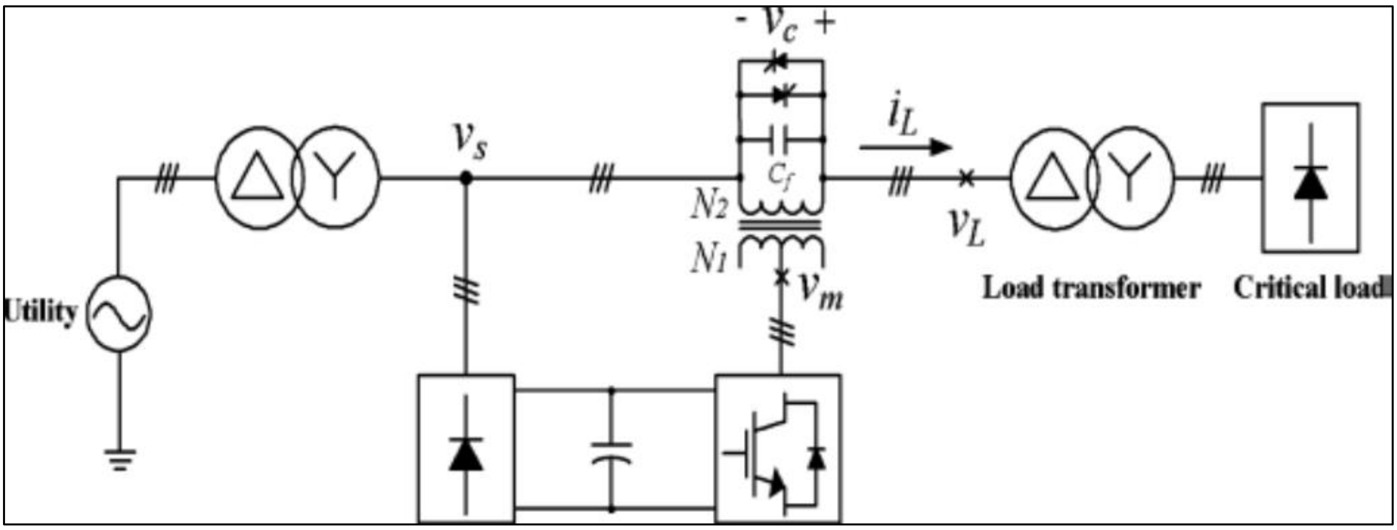

Fig 1 The Offline Series Voltage Sag Compensators Simplified One-Line Schematic.

➢ *Sag Compensator Dynamics Analysis:*

Equivalent circuit representations are employed to examine the dynamic characteristics of the sag compensator shown in Figure 2. Typically, sag compensators allow for as much as 50% of the nominal voltage on the grid by compensating for all three-phase voltages. As a filter, the coupling transformer's inducer can either increase the compensatory voltage or provide electrical isolation. By combining the induction element Lf and the filter capacitor Cf, that are located in the coupling transformer's secondary winding, pulse width modulated (PWM) oscillations are eliminated from the voltage source converter output voltage, Vm.

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➢ *Following is the Formula for Every Dynamic Equation:*

$$L_f \frac{d}{dt}\begin{bmatrix} i_{ma} \\ i_{mb} \\ i_{mc} \end{bmatrix} = \begin{bmatrix} v_{ma} \\ v_{mb} \\ v_{mc} \end{bmatrix} - \begin{bmatrix} v_{ca} \\ v_{cb} \\ v_{c} \end{bmatrix} \quad (1)$$

$$C_f \frac{d}{dt}\begin{bmatrix} v_{ca} \\ v_{cb} \\ v_{cc} \end{bmatrix} = \begin{bmatrix} i_{ma} \\ i_{mb} \\ i_{mc} \end{bmatrix} - \begin{bmatrix} i_{La} \\ i_{Lb} \\ iL_{c} \end{bmatrix} \quad (2)$$

[Vma Vmb Vmc], where T denotes the voltage source converter output voltage, [ima imc]. T, which stands for [vca vcb vcc], This shows the amount of current flowing through the filter inductor. The compensation voltage shown by [iLa iLb iLc] T, while the load current is represented by T. Equations (1) and (2) are converted into the simultaneous referential in the section that follows.

$$\frac{d}{dt}\begin{bmatrix} i^e_{mq} \\ i^e_{md} \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} i^e_{mq} \\ i^e_{md} \end{bmatrix} + \frac{1}{L_f}\begin{bmatrix} v^e_{mq} \\ v^e_{md} \end{bmatrix} - \frac{1}{L_f}\begin{bmatrix} v^e_{cq} \\ v^e_{cd} \end{bmatrix} \quad (3)$$

$$\frac{d}{dt}\begin{bmatrix} v^e_{cq} \\ v^e_{cd} \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} v^e_{cq} \\ v^e_{cd} \end{bmatrix} + \frac{1}{C_f}\begin{bmatrix} i^e_{mq} \\ i^e_{md} \end{bmatrix} - \frac{1}{C_f}\begin{bmatrix} i^e_{Lq} \\ i^e_{Ld} \end{bmatrix} \quad (4)$$

Here, the utility grid's angular frequency is denoted by ω omega, and its representation in the synchronous reference frame is denoted by e. Equations (3) and (4) illustrate how the compensation voltages and the filter inductor current interact.

IV. METHODOLOGY

➢ *Voltage-Current Closed-Loop Control:*

The suggested control approach is shown in Figure 2. For simplicity, the d-axis controller is not displayed. The control block combines the inrush current mitigation technique presented in this study with the complete state-feedback controller**.**

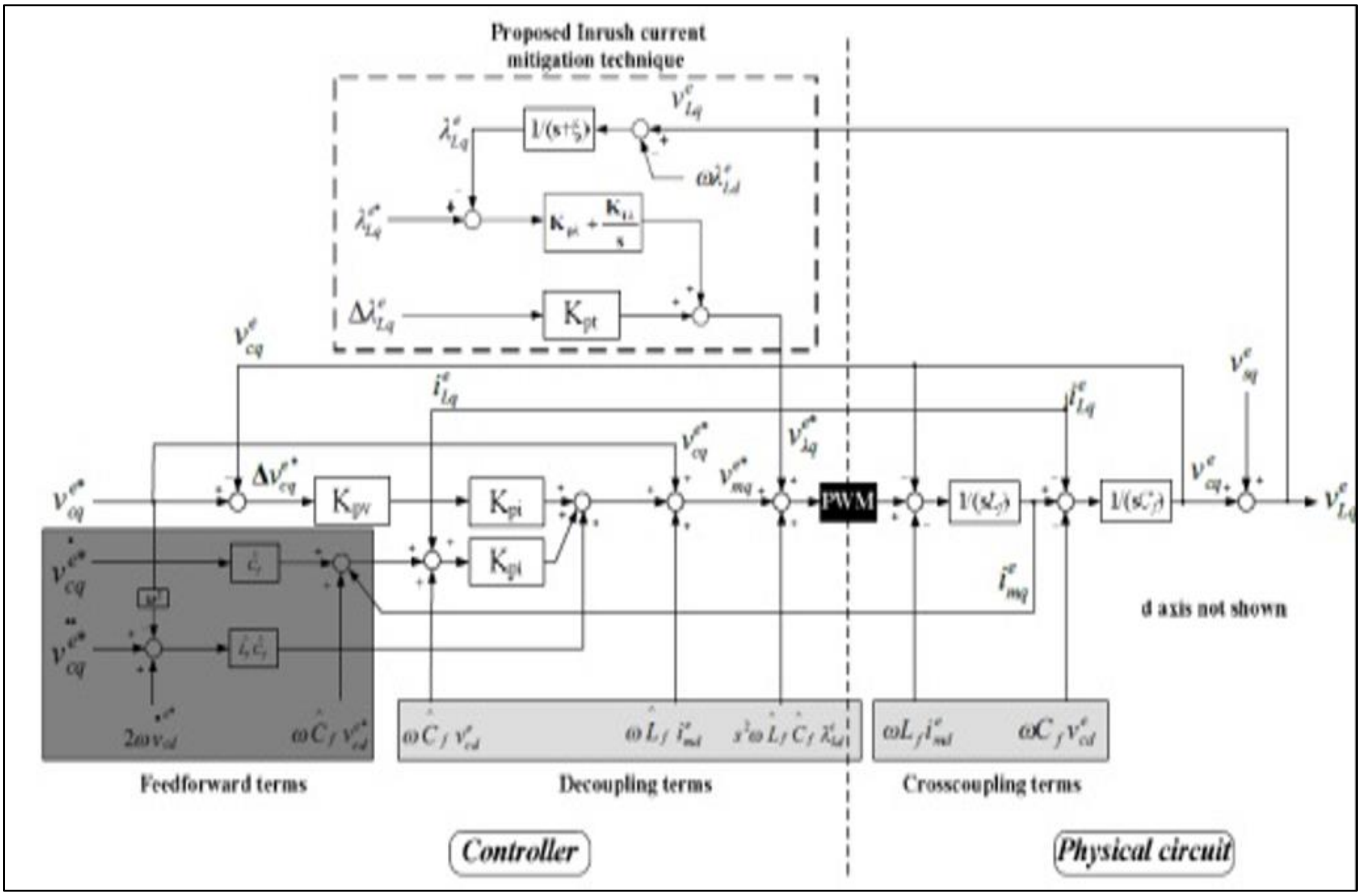

Fig 2 Conceptual Schematic of the State-Feedback Closed-Loop Strategy for Mitigating Transformer Inrush Current.

Ideas of Closed-loop control, decoupling control, and Open-loop compensation are described in this document.

- *Closed-Loop Control:*

The objective of feedback control is to improve robustness in response to parameter changes, enhance disturbance rejection capabilities, and increase the accuracy of compensation for voltage variations. Figure 2 In the proposed control scheme, fast dynamic regulation of the inductor current is achieved through the inner current loop, while the capacitor voltage is stabilized by the outer-loop controller. Indicates that the inductor current is managed by the inner current loop, whereas the capacitor voltage is controlled by the outer voltage loop. A proportional gain Kpv is utilised for voltage control, while the voltage sag compensation technique produces the voltage command. To encourage rapid current tracking, the current control system incorporates a proportional control gain, denoted asaKpi.

- *Feed Forward Control:*

The voltage controller incorporates feed forward control to enhance the voltage sag compensator's dynamic responsiveness. This allows for immediate changes to the load voltage during instances of voltage sag. The compensation voltage, along with the decline in voltage across the filter inductor Lf, can be utilised to calculate the feed forward voltage command.

- *Decoupling Control:*

The cross-coupling terms, as shown through (3) and (4), result from the transformation of the synchronous system frame. The name utilised for decoupling by the controller. To minimise the connection between the d–q axis and prevent cross-coupling. The interaction between the filter inductor current and the capacitor voltage, as well as their respective responsibilities in obtaining the decoupling terms, are depicted in Figure 2.

V. CONCLUSION

The flux linkage difference is caused by the load transformer's damage. Sag voltages can be correctly estimated using a character system technique, which can also show the voltage needed to repair the variation in real time. The flux linkage variation is made up for once the sag compensator operates; the load transformer's risk of inrush current can be successfully prevented. The suggested approach makes use of the voltage and current sensor signals in place; it is simple to combine with the control of the sag compensator's voltage and current. The strategy for regulating transformer flux and compensating voltage sags using a DVR. System is to calculate the compensatory voltage using a fuzzy logic controller. The compensating voltage is continuously regulated to the required magnitude.

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REFERENCES

[1]. P. T. Cheng, W. T. Chen, Y. H. Chen, C. L. Ni, and J. Lin, "A Transformer inrush mitigation method for series Voltage sag Compensators," IEEE Trans. Power Electron. vol. 22, no. 5, pp. Sep. 2007.
[2]. M. S. J. Asghar, "Elimination of inrush current of transformers and distribution lines," in Proc. IEEE Power Electron., Drives Energy Syst. Ind. Growth, 1996, vol. 2, pp. 976–980.
[3]. Y. Cui, S. G. Abdul Salam, S. Chen, and W. Xu, "A sequential Phase energisation technique for transformer inrush current Reduction—Part I: Simulation and experimental results," IEEE Trans. Power Del.., vol. 20, no. 2, pp. 943–949, Apr. 2005.
[4]. W. Xu, S. G. Abdul Salam, Y. Cui, and X. Liu, "A sequential Phase energisation technique for transformer inrush current Reduction—Part II: Theoretical analysis and design guide," IEEE Trans. Power Del.., vol. 20, no. 2, pp. 950–957, Apr. 2005.
[5]. P. C. Y. Ling and A. Basak, "Investigation of magnetising inrush current in a single-phase transformer," IEEE Trans.Magn., vol. 24, no. 6, pp. 3217–3222, Nov. 1988.
[6]. C. Fitzer, A. Arulampalam, M. Barnes, and R. Zurowski, "Mitigation of saturation in the dynamic voltage restorer connection transformers," IEEE Trans. Power Electron., vol. 17, no. 6, pp. 1058–1066, Nov. 2002.
[7]. G. Zenginobuz, I. Cadirci, M. Erims, and C. Barlak, "Performance optimisation of induction motors during voltage-controlled soft starting," IEEE Trans. Energy Convers., vol. 19, no. 2, pp. 278–288, Jun.2004.
[8]. J. Nevelsteen and H. Aragon, "Starting of large motor methods and economics," IEEE Trans. Ind. Appl., vol. 25, no. 6, pp. 1012–1018, Nov./Dec.1989.
[9]. H. Yamada, E. Hiraki, and T. Tanaka, "A novel method of Suppressing the inrush current of transformers uses a series-connected voltage-source PWM converter," in Proc. IEEE Power Electron. Drives Syst. PEDS 2005 Int. Conf., 2006, vol. 1, pp. 280–285. D. L. Brooks and
[10]. D. D. Sabin, "An assessment of distribution system power Quality," Elect. Power Res. Inst.,Palo Alto, CA, EPRI Final Rep. TR-106249-V2, May 1996, vol. 2.
[11]. W. E. rum sickle, R. S. Schneider, G. A. Luckjiff, D. M. Divan, and M. F. McGranaghan, "Dynamic sag correctors: Cost-effective industrial power line conditioning," IEEE Trans. Ind. Appl., vol. 37, no. 1, pp. 212–217, Jan./Feb. 2001.
[12]. N. H. Woodley, "Field experience with dynamic voltage restorer (DVRTMMV) systems," in Proc. IEEE Power Eng. Soc. Winter Meeting, Jan. 23–27, 2000, vol. 4, pp. 2864–2871.
[13]. D. Sabin, An assessment of distribution system power quality, Elect. Power Res. Inst., Palo Alto, CA, EPRI Final Rep. TR-106249-V2, vol. 2, Statistical Summary Report, May 1996.
[14]. C. J. Huang, S. J. Huang, F. S. Pai, Design of dynamic voltage restorer with disturbance-filtering enhancement, IEEE Transactions on Power Electronics, vol.18, pp.1202-1210, Sept. 2003.
[15]. P. K. Lim, D.S. Dorr, Understanding and resolving voltage sag related problems for sensitive industrial customers, IEEE Power Engineering Society Winter Meeting, vol.4, pp.2886-2890, 2000.
[16]. P. T. Cheng, C. L. Ni, J. M. Chen, Design of a state feedback controller for series voltage sag compensators, Power Conversion Conference, pp. 398-403, April 2007.
[17]. Po-Tai Cheng An Inrush Mitigation Technique Of load Transformers For The Series Voltage Sag Compensator978-4244-1668-4/08/$25.00 2008 IEEE.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26jan321

[18]. Yogesh K Chauhan Bhavnesh Kumar and Sajid Ali.GBU Study and Performance of DVR for Voltage Quality Enhancement 987-1-4673-6150-7/13IEEE2013.
[19]. Ajinkya M. Bhaware, 2M.F.A.R Satarkar Series Transformer Inrush Mitigation Technique during Change in Load for Distribution System Proceedings of 32nd IRF International Conference, 12th July 2015, Pune, India, ISBN: 978-93-85465-54-3.
[20]. Venkatesh Dugyala, Ch.Nagalaxmi, V.K.R.Mohan Rao A Novel Control Strategy to Reduce Transformer Inrush Currents by Series Voltage Sag Compensator Science International Journal of Engineering Research and Development ISSN: 2278-067X, P-ISSN: 2278-800X,Volume 8, Issue 5 (August 2013), PP. 54-63.