Cite this article

Lei H, Zheng X, Sang Z *et al.* (2021)
Magnetic flux control in an urban distribution network based on load optimisation.
Proceedings of the Institution of Civil Engineers – Energy **174**(2): 49–56,
<https://doi.org/10.1680/jener.19.00012>

Research Article

Paper 1900012
Received 12/02/2019;
Accepted 10/03/2020;
Published online 28/04/2020

Keywords: electrical engineering &
distribution/energy conservation/power

ICE Publishing: All rights reserved

Energy

ICE Publishing

Magnetic flux control in an urban distribution network based on load optimisation

He Lei

State Grid Laboratory for Hydro-thermal Power Resources Optimal Allocation & Simulation Technology, State Grid HBEPC Ltd., Economic & Technology Research Institute, Wuhan, China
(corresponding author: regallyhust@hotmail.com)
(Orcid:0000-0001-5600-7816)

Xu Zheng

State Grid Laboratory for Hydro-thermal Power Resources Optimal Allocation & Simulation Technology, State Grid HBEPC Ltd., Economic & Technology Research Institute, Wuhan, China

Zixia Sang

State Grid Laboratory for Hydro-thermal Power Resources Optimal Allocation & Simulation Technology, State Grid HBEPC Ltd., Economic & Technology Research Institute, Wuhan, China

Rengcun Fang

State Grid Laboratory for Hydro-thermal Power Resources Optimal Allocation & Simulation Technology, State Grid HBEPC Ltd., Economic & Technology Research Institute, Wuhan, China

Jiong Yan

State Grid Laboratory for Hydro-thermal Power Resources Optimal Allocation & Simulation Technology, State Grid HBEPC Ltd., Economic & Technology Research Institute, Wuhan, China

Yingxiang Wang

State Grid Laboratory for Hydro-thermal Power Resources Optimal Allocation & Simulation Technology, State Grid HBEPC Ltd., Economic & Technology Research Institute, Wuhan, China

Zhi Du

State Grid Laboratory for Hydro-thermal Power Resources Optimal Allocation & Simulation Technology, State Grid HBEPC Ltd., Economic & Technology Research Institute, Wuhan, China

Dongjun Yang

State Grid Laboratory for Hydro-thermal Power Resources Optimal Allocation & Simulation Technology, State Grid HBEPC Ltd., Economic & Technology Research Institute, Wuhan, China

Jingyou Xu

State Grid Laboratory for Hydro-thermal Power Resources Optimal Allocation & Simulation Technology, State Grid HBEPC Ltd., Economic & Technology Research Institute, Wuhan, China

Lei Wu

SG Huangshi Electric Power Supply Company, Huangshi, China

This paper proposes a control method for eliminating direct current (DC) flux from the isolation transformer of a customer service device to avoid magnetic saturation. The method is characterised by injecting zero compensation voltage during a designed time. The period during which no compensation voltage is injected is minimised by adjusting the normal compensation time in the initial stage. For a customer service device, such as a dynamic voltage restorer, the reverse turn-off voltage will introduce extra initial flux. The calculation process based on a trigonometric function also takes into account the effects of the initial flux. The experimental results verify the proposed method to prevent DC flux to the isolation transformer.

Notation

N	turn number of the secondary (supply side) winding in the series transformer
t_0	ending of turn-off voltage
t_1	ending of first-stage compensation
t_2	ending of second-stage compensation
V_0	amplitude of turn-off voltage
V_1	amplitude of injection voltage
α	initial angle of injection voltage
ϕ	magnetic flux
ω	angular frequency

1. Introduction

With the gradual depletion of fossil fuels and increasing environmental pollution, a new round of energy revolution integrating information technology, internet technology and energy technology is slowly beginning (de Boer and Zuidema, 2015). The energy internet emphasises the characteristics of substitution, coordination, integration and interaction and has

different performances at all levels (Kirkman *et al.*, 2010). The energy internet utilizes renewable energy as the main primary energy, supports large-scale distributed energy resources (DER) access and realises wide-area energy sharing by relying on internet technology. The energy internet takes the large power grid as the ‘backbone network’. It strategically lays out the interconnection of energy across continents through ultra-high-voltage (UHV) and AC/DC transmission technology in the generation and transmission links, and constructs the global energy internet. In the distribution and utilisation links, distributed energy and micro-network units are used as ‘local area networks’ (Hannan *et al.*, 2018). Urban energy internet is constructed by utilising the mutual transformation and substitution of electricity, gas, cold and heat energy (Wei *et al.*, 2017). An energy router is used as an intelligent control unit to realise bidirection on-demand transmission and dynamic balanced use of energy.

The integrated distribution system is a power distribution system with an integrated power distribution network and a

big data information system, integrated power generation and consumption and 'internet+' business mode, which is integrated and coordinated with the wide area 'source, network, and storage' (Lin *et al.*, 2018: p. 5918). The goal of multi-source coordinated optimisation control service is to provide operational decision making for the safety, economy and optimal operation of an active distribution network through regional autonomy and global optimisation.

The permeability of distributed energy such as photovoltaic (PV), wind turbines (WT), micro-turbines (MT), energy storage systems (ESS), electric vehicles (EV), cogeneration of cooling, heating and power (CCHP) and so on (Arshad and O'Kelly, 2018; French *et al.*, 2005; Lühn and Geldermann, 2018; Shivkumar *et al.*, 2016; Teng *et al.*, 2015) is constantly increasing in the power system, which puts forward higher requirements for the security, reliability and economic operation ability of the power system, especially the distribution network. Therefore, an active distribution network is considered as an effective way to solve the problem of distributed energy access in a power system and even the energy internet (Wang *et al.*, 2018). By upgrading the existing distribution network and building an active distribution network, the ability to optimise the allocation of the regional energy transmission network can be greatly improved, the flexible access and absorption of high-permeability distributed energy in the demonstration area can be supported, the coordinated optimisation of multiple energy sources can be realised and the safe and efficient utilisation of regional energy can be improved (Koutsoukis *et al.*, 2017).

A multi-energy complementary integrated energy system will be an important technology development direction of the energy industry in the future (Huo *et al.*, 2017). Urban industrial parks are the main battlefield of integrated energy services and business innovation. In the active energy interconnection distribution network of urban industrial parks, a large number of distributed generation units will change from a traditional radial network to a network comprising a large number of small- and medium-sized interconnections, which is also the main force to promote the transformation of energy structure (Zhang *et al.*, 2017).

With the prominence of power quality problems, the application of custom power technology in high-quality industrial parks is accelerated (Domijan *et al.*, 2005; Moayed *et al.*, 2018). Advanced power electronic devices such as the static transfer switch (STS), distribution static synchronous compensator (DSTATCOM), low-voltage/medium-voltage dynamic voltage restorer (LV/MVDVR) and uninterruptible power supply (UPS) are connected to the energy interconnected active distribution network of industrial parks (Li *et al.*, 2018). Figure 1 shows the morphology diagram of an energy interconnected active distribution network in urban industrial park. The basic unit of active

management of distributed power supply in a power grid is the converter. To satisfy the electrical isolation, the converter must pass through an isolation transformer to connect to the power grid. Taking dynamic voltage restoration (DVR) to resist voltage sag as an example, the access of DVR needs a series coupling transformer to realise electrical isolation. When voltage sag occurs, the initial angle of DVR injection voltage is random, so it may cause a DC flux, even magnetic saturation – that is, a great inrush current. In this case, the relevant protection devices may malfunction, making DVR unable to work properly.

To avoid such a situation, some manufacturers intentionally increased the saturation magnetic induction intensity of the transformer core, but the cost also increased. Therefore, some research institutions and scholars chose to use control strategies to avoid magnetic saturation of the transformer. A limiter was installed between the transformer and the inverter to regulate the current (Arbolea *et al.*, 2009). Another transformer with a controllable auxiliary winding was installed (Molcrette *et al.*, 1998). Overall, these methods increase hardware costs. The more economical way is to adjust the amplitude and phase of the injection voltage to avoid magnetic saturation of the transformer. When the initial angle of the injection voltage is $\pm 90^\circ$, there will be no DC flux in the transformer, that is to say, no adjustment methods are needed. However, if the peak time is missed, it may take up to half a cycle to compensate the loads. For some devices, the drop of half a cycle is unacceptable. Therefore, the alternative way is to reduce the injection voltage amplitude by half in the first half-cycle. Fitzer *et al.* (2002) designed an adaptive coefficient based on the amplitude and initial angle of compensation voltage to adjust the amplitude of compensation voltage. Jimichi *et al.* (2008) intentionally interrupted the compensation for the one-sixth cycle instead of normal compensation to eliminate DC flux. Gao *et al.* (2012) used a shorter zero-amplitude time to eliminate DC flux near the peak time. Gao *et al.* (2015) combined flux control with voltage control to avoid magnetic saturation, but the design complexity of controller parameters will be greatly improved. The topology of DVR is shown in Figure 2.

For DVR, an effective compensation can only be realised by switching off the thyristor quickly. As the thyristor cannot be switched off naturally until the current passes zero, a reverse voltage needs to be injected to turn off the thyristor quickly. This reverse voltage also increases the initial flux, which is not considered in several studies in the literature (Arbolea *et al.*, 2009; Gao *et al.*, 2012, 2015; Jimichi *et al.*, 2008). Therefore, starting from the angle of controlling the voltage amplitude, this paper takes the turn-off voltage into account, establishes the mathematical model of flux, minimises the time of zero-amplitude compensation by adjusting the normal compensation time in the initial stage, eliminates the DC flux and reduces the impact on the load.

Figure 1. Morphology diagram of energy interconnected active distribution network in urban industrial parks. APF, active power filter

2. Modelling

An equivalent one-line diagram of a three-phase DVR is shown in Figure 3. When the power grid is in normal operation, the thyristor is on and the DVR is in bypass mode. When voltage sag occurs, the thyristor is off and the DVR is in operation mode. Due to the relatively small leakage inductance and reactance of the transformer, the flux induced in the series transformer is calculated as

$$1. \quad \phi = \frac{1}{N} \int_0^t V_1 \sin(\omega t + \alpha) = \frac{V_1}{\omega N} \cos \alpha - \frac{V_1}{\omega N} \cos(\omega t + \alpha)$$

It can be found that the DC component of the flux is zero when the initial phase is $\pm 90^\circ$. When the initial phase is 0 or 180° , the DC component of the flux is the largest, and the maximum value of the flux is twice that of the steady state. In this case, the inrush current is larger.

Considering that the turn-off voltage of the thyristor also generates flux, the actual flux induced in the transformer is shown as

$$2. \quad \begin{aligned} \phi &= \frac{V_0 t_0}{N} + \frac{1}{N} \int_{t_0}^t V_1 \sin(\omega t + \alpha) \\ &= \frac{V_0 t_0}{N} + \frac{V_1}{\omega N} \cos(\omega t_0 + \alpha) - \frac{V_1}{\omega N} \cos(\omega t + \alpha) \end{aligned}$$

The operating principle of this unlimited method is shown in Figure 4(a). In this case, due to the extra initial flux caused by the turn-off voltage, some amplitude adjustment methods proposed previously in the literature cannot achieve the desired results.

3. Proposed method for eliminating DC flux

The method of eliminating DC flux by adjusting the magnitude of the injection voltage is generally divided into three stages. In the first stage, the normal compensation voltage is

injected first, and then the compensation voltage is zero in the second stage. In the third stage, the normal continuous compensation is started. The duration of the first two stages is calculated according to the characteristics of a trigonometric

Figure 2. DVR typical topology. PCC, point of common coupling; VSI, voltage source inverter

Figure 3. Equivalent one-line diagram of a three-phase DVR

function, which is generally a fixed value (Gao *et al.*, 2012; Jimichi *et al.*, 2008). The initial flux generated by turn-off voltage will break the law of the trigonometric function, which makes it difficult to calculate a fixed value. Moreover, the shorter the time of the second stage, the smaller the impact on the load. Therefore, a new approach to eliminate DC flux is proposed in this paper. By adjusting the duration of the first stage, the zero compensation time can be the shortest, and the DC flux can be eliminated after zero compensation.

As shown in Figure 4(b), from $t=0$ to t_0 , the DVR provides the turn-off voltage V_0 . From $t=t_0$ to t_1 (first stage), the DVR provides full compensating voltage V_1 . From $t=t_1$ to t_2 (second stage), the DVR injects no compensating voltage, the flux induced in the transformer is expressed as

$$\begin{aligned} \phi(t) &= \frac{V_0 \times t_0}{N} + \frac{1}{N} \int_{t_0}^{t_1} V_1 \sin(\omega t + \alpha) + \frac{1}{N} \int_{t_1}^t V_1 \sin(\omega t + \alpha) \\ 3. \quad &= \frac{V_0 \times t_0}{N} + \frac{V_1}{\omega N} \cos(\omega t_0 + \alpha) - \frac{V_1}{\omega N} \cos(\omega t_1 + \alpha) \\ &+ \frac{V_1}{\omega N} \cos(\omega t_2 + \alpha) - \frac{V_1}{\omega N} \cos(\omega t + \alpha) \end{aligned}$$

To eliminate DC flux after zero compensation, the DC component in the above equation should be zero.

$$\begin{aligned} 4. \quad &\frac{V_0 \times t_0}{N} + \frac{V_1}{\omega N} \cos(\omega t_0 + \alpha) \\ &- \frac{V_1}{\omega N} \cos(\omega t_1 + \alpha) + \frac{V_1}{\omega N} \cos(\omega t_2 + \alpha) = 0 \end{aligned}$$

Figure 4. Principle of proposed method: (a) magnetic flux without limitation; (b) magnetic flux with proposed method

Assuming $\Delta t_2 = t_2 - t_1$ and $\Delta t_1 = t_1 - t_0$, the above equation can be rewritten as

$$5. \quad \cos(\omega t_0 + \alpha + \omega \Delta t_1 + \omega \Delta t_2) = \cos(\omega t_0 + \alpha + \omega \Delta t_1) - \cos(\omega t_0 + \alpha) - \frac{\omega t_0 V_0}{V_1}$$

By solving the above equation, the expression of the duration of the second stage can be obtained as

$$6. \quad \Delta t_2 = \frac{1}{\omega} \arccos \left[\cos(\omega t_0 + \alpha + \omega \Delta t_1) - \cos(\omega t_0 + \alpha) - \frac{\omega t_0 V_0}{V_1} \right] - \Delta t_1 - t_0 - \frac{\alpha}{\omega}$$

To minimise the time of the second stage (zero compensation) as much as possible, it is necessary to adjust Δt_1 to minimise Δt_2 , so the derivative of Δt_2 is obtained to solve its minimum value.

$$7. \quad \frac{d\Delta t_2}{d\Delta t_1} = \frac{\sin(\omega t_0 + \alpha + \omega \Delta t_1)}{\sqrt{1 - [\cos(\omega t_0 + \alpha + \omega \Delta t_1) - \cos(\omega t_0 + \alpha) - (\omega t_0 V_0 / V_1)]^2}} - 1 = 0$$

The above equation can be solved as

$$8. \quad \cos(\omega t_0 + \alpha) + \frac{\omega t_0 V_0}{V_1} = 2 \times \cos(\omega t_0 + \alpha + \omega \Delta t_1)$$

By solving the above equation, the expression of the duration of the first stage can be written as

$$9. \quad \Delta t_1 = \frac{1}{\omega} \arccos \left\{ \frac{1}{2} \left[\cos(\omega t_0 + \alpha) + \frac{\omega t_0 V_0}{V_1} \right] \right\} - t_0 - \frac{\alpha}{\omega}$$

Combining Equation 6, the expression of the duration of the second stage can be presented as

$$10. \quad \Delta t_2 = \frac{1}{\omega} \arccos \left[\cos(\omega t_0 + \alpha + \omega \Delta t_1) - \cos(\omega t_0 + \alpha) - \frac{\omega t_0 V_0}{V_1} \right] - \frac{1}{\omega} \arccos \left\{ \frac{1}{2} \left[\cos(\omega t_0 + \alpha) + \frac{\omega t_0 V_0}{V_1} \right] \right\}$$

4. Experimental results

A three-phase 10 kW LVDVR prototype, as shown in Figure 5, has been developed to verify the method presented in the previous section. A double-loop feedback control strategy with reference voltage feed-forward is applied in the DVR. The voltage sag is simulated in the laboratory by a voltage sag generator (VSG).

Figures 6–9 show the experimental waveforms. The magnetic flux density which is scaled by 0.5 T/div is calculated by Matlab software using the voltage sampled by Tektronix TDS 2014C at 50 kHz sampling rate, and redrawn by using WaveStar software.

Figures 6 and 7 indicate the grid voltage dropped 50%, and the DVR injects compensation voltage when sag occurs at the angle of 0°. The sag detect time is 2.6 ms. The amplitude of thyristor turn-off voltage is –100 V, and the duration time is 1 ms. As shown in Figure 6, because no means of adjustment have been used, the DC bias of the transformer is 0.1 T.

Whereas, in Figure 7, by the means of the proposed method, the compensation voltage is interrupted for 0.7 ms (second stage) after 1 ms (first stage) of normal compensation to avoid producing DC magnetic flux.

Figure 5. Laboratory prototype of the DVR system. VSG, voltage sag generator

Figure 6. Experimental results without limitation when sag occurs at 0°

Figure 7. Experimental results with proposed method when sag occurs at 0°

Figures 8 and 9 indicate the grid voltage dropped 50%, and the DVR injects compensation voltage when sag occurs at the angle of 90° . The sag detect time is 1.8 ms. The amplitude of thyristor turn-off voltage is -100 V, and the duration time is

1 ms. As shown in Figure 8, because no means of adjustment have been used, the DC bias of the transformer is -0.5 T. In this worst case, the amount of the DC flux is equal to the amplitude of the AC flux.

Figure 8. Experimental results without limitation when sag occurs at 90°

Figure 9. Experimental results with proposed method when sag occurs at 90°

Whereas, in Figure 9, by the means of the proposed method, the compensation voltage is interrupted for 3.2 ms (second stage) after 5.6 ms (first stage) of normal compensation to avoid producing DC magnetic flux.

5. Conclusion

This paper has proposed a control method for eliminating DC flux from the isolation transformer of a customer service device. The DC flux is eliminated by injecting zero

compensation voltage for the minimum possible time. The period of no compensation is calculated by trigonometric function for the goal of minimum voltage drop on the load. The calculation process takes the initial flux that is introduced by reverse turn-off voltage into account to make the calculation more accurate. A 400 V–10 kW laboratory system has been established to verify the effectiveness of the proposed method. The experimental results in two situations prove that the DC flux is eliminated effectively.

REFERENCES

- Arbolea P, Diaz D, Gonzalez MC, Coto J and Gomez AJ (2009) An inrush current limiter as a solution of injection transformer oversizing in dynamic voltage restorer. *International Conference on Electrical Machines and Systems, Tokyo, Japan*, pp. 1–6.
- Arshad M and O'Kelly BC (2018) Diagnosis of electricity crisis and scope of wind power in Pakistan. *Proceedings of the Institution of Civil Engineers – Energy* **171**(4): 158–170, <https://doi.org/10.1680/jener.17.00021>.
- de Boer J and Zuidema C (2015) Towards an integrated energy landscape. *Proceedings of the Institution of Civil Engineers – Urban Design and Planning* **168**(2): 231–240.
- Domijan A, Montenegro A, Keri AJF and Mattern KE (2005) Custom power devices: an interaction study. *IEEE Transactions on Power Systems* **20**(2): 1111–1118.
- French R, Bonnett D and Sardon J (2005) Wind power: a major opportunity for the UK. *Proceedings of the Institution of Civil Engineers – Civil Engineering* **158**(6): 20–27.
- Fitzler C, Arulampalam A, Barnes M and Zurewski R (2002) Mitigation of saturation in dynamic voltage restorer connection transformer. *IEEE Transaction on Power Electronics* **17**(6): 1058–1066.
- Gao S, Lin XC, Kang Y, Duan YP and Qiu J (2012) Mitigation of inrush current in dynamic voltage restorer injection transformers. *IEEE Energy Conversion Congress and Exposition, Raleigh, NC, USA*, pp. 4093–4098.
- Gao S, Lin XC, Ye SJ, Lei H and Kang Y (2015) Transformer inrush mitigation for dynamic voltage restorer using direct flux linkage control. *IET Power Electronics* **8**(11): 2281–2289.
- Hannan MA, Faisal M, Ker PJ et al. (2018) A review of internet of energy based building energy management systems: issues and recommendations. *IEEE Access* **6**: 38997–39014.
- Huo ML, Huang XD, Xu YS and Li WY (2017) Regional energy planning – an example of Suzhou industrial park. *2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China*, pp. 1–5.
- Jimichi T, Fujita H and Akagi H (2008) An approach to eliminating DC magnetic flux from the series transformer of a dynamic voltage restorer. *IEEE Transaction on Industry Application* **44**(3): 809–816.
- Kirkman R, Duval D and Stephens D (2010) Sheffield energy recovery facility and district energy network. *Proceedings of the Institution of Civil Engineers – Energy* **163**(2): 69–78, <https://doi.org/10.1680/jener.2010.163.2.69>.
- Koutsoukis NC, Siagkas DO, Georgilakis PS and Hatziaargyriou ND (2017) Online reconfiguration of active distribution networks for maximum integration of distributed generation. *IEEE Transactions on Automation Science and Engineering* **14**(2): 437–448.
- Li R, Wang W and Xia MC (2018) Cooperative planning of active distribution system with renewable energy sources and energy storage systems. *IEEE Access* **6**: 5916–5926.
- Lin CK, Deng DJ, Kuo CC and Liang YL (2018) Optimal charging control of energy storage and electric vehicle of an individual in the internet of energy with energy trading. *IEEE Transactions on Industrial Informatics* **18**(6): 2570–2578.
- Lühn T and Geldermann J (2018) Optimising power grids using batteries and fuzzy control of photovoltaic generation. *Proceedings of the Institution of Civil Engineers – Energy* **171**(1): 32–36, <https://doi.org/10.1680/jener.17.00005>.
- Moayed M, Masoum MAS, Fereidouni A and Deilami S (2018) Optimal sizing, siting and operation of custom power devices with STATCOM and APLC functions for real-time reactive power and network voltage quality control of smart grid. *IEEE Transactions on Smart Grid* **9**(6): 5564–5575.
- Molcrette V, Kotny JL, Swan JP and Brudny JF (1998) Reduction of inrush current in single-phase transformer using virtual air gap technique. *IEEE Transaction on Magnetics* **34**(4): 1192–1194.
- Shivkumar K (2016) Back to the future: lessons for internet of energy networks. *IEEE Internet Computing* **20**(1): 60–65.
- Teng F, Pudjianto D, Strbac G et al. (2015) Potential value of energy storage in the UK electricity system. *Proceedings of the Institution of Civil Engineers – Energy* **168**(2): 107–117, <https://doi.org/10.1680/jener.14.00033>.
- Wang D, Liu L, Jia HJ et al. (2018) Review of key problems related to integrated energy distribution systems. *CSEE Journal of Power and Energy Systems* **4**(2): 130–145.
- Wei W and Dai G (2017) Research of urban energy internet's key technologies and its application. *2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China*, pp. 1–6.
- Zhang WY, Shen PF and Xiao J and Wang CN (2017) Zonal-voltage control for active distribution network based urban energy internet with distributed static synchronous compensator and distributed generator. *2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China*, pp. 1–6.

How can you contribute?

To discuss this paper, please email up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial board, it will be published as discussion in a future issue of the journal.

Proceedings journals rely entirely on contributions from the civil engineering profession (and allied disciplines). Information about how to submit your paper online is available at www.icevirtuallibrary.com/page/authors, where you will also find detailed author guidelines.