REACTIVE POWER COMPENSATION CAPABILITY OF A BATTERY ENERGY STORAGE PLANT

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Abstract - A battery energy storage plant is increasingly accepted and widely used in electric power distribution systems in a near future to enable energy arbitrage during the peak/off-peak hours. Large voltage fluctuation and energy losses can cause inefficient operation of electric power distribution systems. In this paper, ability to manipulate the reactive power of the battery plant is analyzed and studied. Limitations of reactive power compensation for each battery storage plant are formulated and depicted to exhibit its ability to help overall distribution system. A 22-kV local power distribution feeder in Nakhon Ratchasima, Thailand is selected as a test system. As a result, the battery storage plant can compensate the reactive power up to 4 – 5 Mvar with the equivalent source reactance being 0.01 W.

Keywords - Aluminium Alloys, Plasma Spray, Thermal Barrier Coatings, Thermal Fatigue, Yttria-Zirconia.

I. INTRODUCTION

Large-scale power plants have historically been utilized to provide ancillary services to ensure the distribution networks operate steadily [1].However, the recent rise in renewable energy sources (RESs) has had an impact on the power networks' operational plans. There are technical and operational difficulties brought on by the intermittent operation of RESs in current power utility grids [2].Due to intermittent generation and its impact on the demand and generation balance, the high degree of penetration, especially in the transmission grids, has the potential to drastically modify the bulk power system and cause unique frequency variations.However, the recent rise in renewable energy sources (RESs) has had an impact on the power networks' operational plans. There are technical and operational difficulties brought on by the intermittent operation of RESs in current grids [3].On the other hand, the distribution grid's active power injections from distributed RESs can cause technical problems such voltage violations, power fluctuations, and network congestion [4].Due to the growing adoption of centralized and distributed RESs, which lowers their overall capacity to provide ancillary services, traditional power plants are rapidly being decommissioned [5]. This paper organizes five sections. Section 2 is Problem Formulation to describe a structural circuit of a battery energy storage system.

II. PROBLEM FORMULATION

2.1. Battery Energy Storage System

Rechargeable batteries known as Battery Energy Storage Systems, or BESS, are able to store energy from a variety of sources and discharge it as needed. BESS, which can be used to balance the electric grid, provide backup power, and enhance grid stability, is made up of one or more batteries.Comparing battery storage systems to conventional grid storage solutions, there are significant advantages.BESS provides extremely effective and affordable energy storage solutions for all types of energy users, including offshore drilling platforms or vessels, traditional thermal power plant operators, grid operators, and producers of renewable energy.BESS enables energy arbitrage, allowing to directly lower electricity bills by peak shaving or potentially create new cash streams.Power electronics-based converters are used to link battery storage systems to the AC distribution grid as shown in Fig. 1.

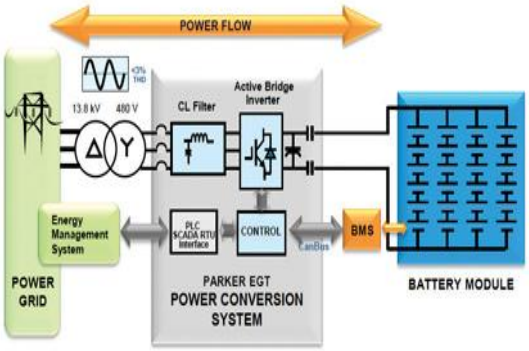


Fig.1. Battery energy storage interfacing circuit

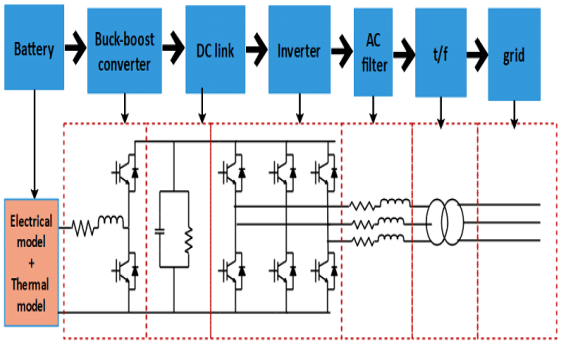


Fig.2. Battery energy storage interfacing circuit

An isolating transformer is typically used in three-phase power electronic conversion systems to provide an input AC/DC inverter as in Fig. 2. The lithium-ion battery storage modules can be fully controlled with a DC link capacitor and a DC/DC converter to manage its DC link voltage. Reactive power compensation mode states that when a PWM converter is utilized, a current drawn from a point of coupling connection can be adjusted to be in-phase with the terminal voltage (unity power factor condition) or even to a leading phase angle. This indicates that reactive power drawn from the point of connection can be controlled by the PWM inverter.

A PWM controller is often built to function at the highest power factor achievable.Although this technique works quite well in terms of not taking reactive power from the power supply, it does nothing to balance the overall system where some other loads still draw a significant amount of reactive power.Consequently, the expensive power compensator is necessary. However, when the reactive power is brought on by a poor power-factor load that is placed far from the compensator position, the power compensator occasionally fails to perform compensation properly. In this situation, voltage drops and power losses are severe.With PWM control, the BESS can help compensate the excess reactive power for the entire feeding section. This leads to more efficient reactive power compensation.

2.2. Reactive Power Compensation Limit

The power compensator, such as capacitor bank, etc, is special equipment designed primarily to supply reactive power to the system.Compared to a normal PWM inverter of the BESS, it has a greater range of reactive power capacity. However, this drawback will be minimized or taken away if the PWM power inverters are specifically constructed for compensating purpose.

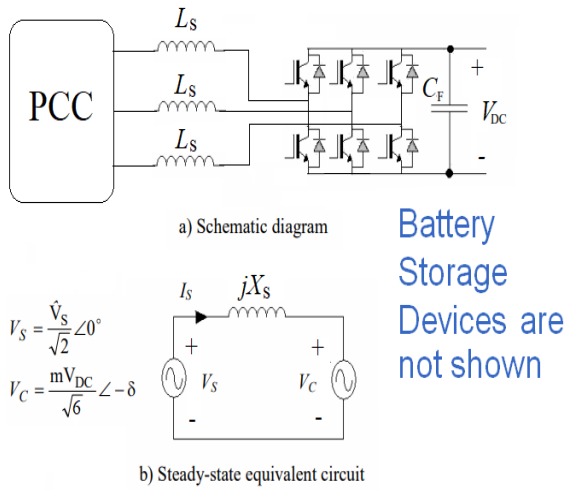


Fig.3. PWM power inverter interfacing circuit

Consider Fig. 3,a three-phase lossless PWM power inverter. The corresponding circuit built for the fundamental frequency as illustrated in Fig. 3 can effectively represent the PWM inverter's performance under steady-state conditions even if it uses non-linear switched-mode operation [6].

The voltage source, V_S, represents the rated voltage of the point of coupling connection.Therefore, real and reactive power flows transfer, P_S and Q_S,through the PWM inverter can be obtained from the following expressions.

$$P_s = \frac{m\widehat{V_s}V_{DC}}{\sqrt{12}X_s}\sin\delta \quad (1)$$

$$Q_s = \frac{\widehat{V_s}^2}{2X_s} - \frac{m\widehat{V_s}V_{DC}}{\sqrt{12}X_s}\cos\delta \quad (2)$$

Where
$\widehat{V_S}$ is a peak magnitude of the input voltage
X_S is a source reactance
V_{DC} is a level of DC link voltage
m is modulation index of the controller
d is phase angle of the controller

Reactive power flow through the PWM power inverter must be changeable while the real power demand is separately regulated for it to function as a reactive power compensator. Reactive power can be rewritten as in (4) assuming that the real power requirement of the inverter is constant as stated in (3).

$$P_s = \widetilde{P_s} \quad (3)$$

$$Q_s = \frac{\widehat{V_s}^2}{2X_s} - \frac{\widetilde{P_s}}{\tan\delta} \quad (4)$$

Undoubtedly, the reactive power is influenced by four major factors: Input reactance, real power demand, voltage magnitude of the PCC, phase angle of the modulating waveform with respect to the carrier waveform.While the interfacing voltage magnitude and its input reactance are assumed to be constant, the real power consumption is fixed. Therefore, only dis available for controlling reactive power.Thus,

$$Q_{s,min} = \frac{\widehat{V_s}^2}{2X_s} - \frac{\widetilde{P_s}}{\tan\delta_{min}} \quad (5)$$

$$Q_{s,max} = \frac{\widehat{V_s}^2}{2X_s} - \frac{\widetilde{P_s}}{\tan\delta_{max}} \quad (6)$$

$$\delta_{min} = \sin^{-1}\left(\frac{\sqrt{12}X_s\widetilde{P_s}}{m_{max}\widehat{V_s}V_{DC}}\right) \quad (7)$$

$$\delta_{max} = \sin^{-1}\left(\frac{\sqrt{12}X_s\widetilde{P_s}}{m_{min}\widehat{V_s}V_{DC}}\right) \quad (8)$$

With varying m and δ subject to constant real power operation, the phasor diagram for all feasible operating regions consisting of lagging, unity and leading power factors is formed in Fig.4.

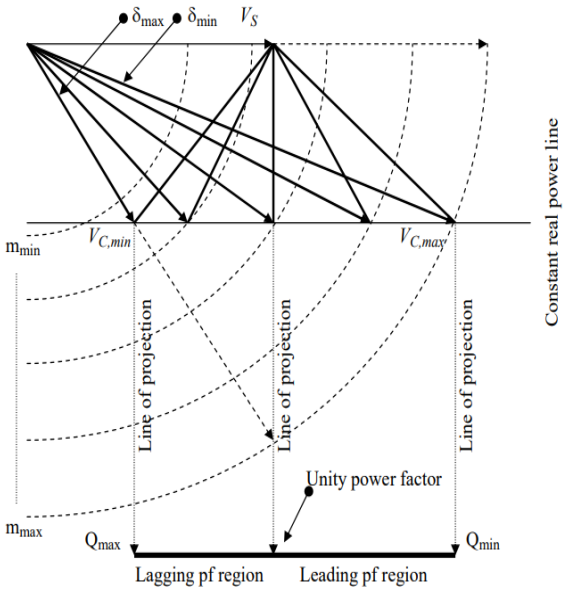


Fig.4. Feasible operating region for constant real power operation

III. RESULTS AND DISCUSSION

3.1. Simple BESS Plant

Suppose that a PWM inverter of the BESS plant has the following parameters: V_{DC}=600-1500 V, $\widehat{V_s}$=294-359 V, m=0.45-0.95 for a typical PWM inverter. Assume the source reactanceX_S, 0.1 p.u. with the base impedance of 0.16 W. Therefore, the source reactanceX_s = 0.016 W.Practically, this value is too small. Let $\widetilde{P_s} = 500$ kW, $\widehat{V_s}$=300 V and V_{DC}=1200 V, hence

$$\delta_{min} = \sin^{-1}\left(\frac{\sqrt{12}X_s\widetilde{P_s}}{m_{max}\,\widehat{V_s}V_{DC}}\right) = 4.65° \quad (9)$$

$$\delta_{max} = \sin^{-1}\left(\frac{\sqrt{12}X_s\widetilde{P_s}}{m_{min}\,\widehat{V_s}V_{DC}}\right) = 9.85° \quad (10)$$

$$Q_s = \frac{\widehat{V_s}^2}{2X_s} - \frac{\widetilde{P_s}}{\tan\delta} = 2812.5 - \frac{500}{\tan\delta}\ \text{kvar} \quad (11)$$

(11) can be plotted as shown in Fig.5. This curve is quite impressive but the curve is shifted to the vertical axis according to the real power changed as shown in Fig. 6.

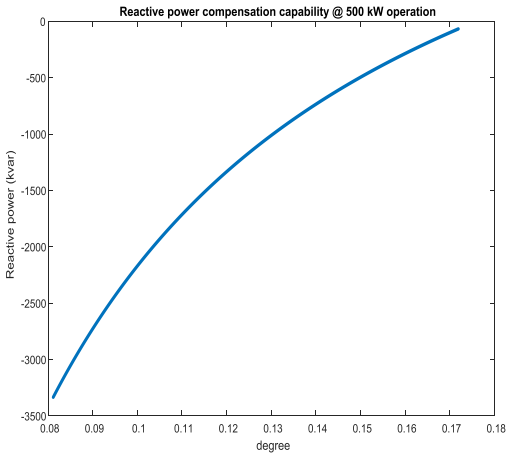


Fig.5. Reactive power limit of the circuit

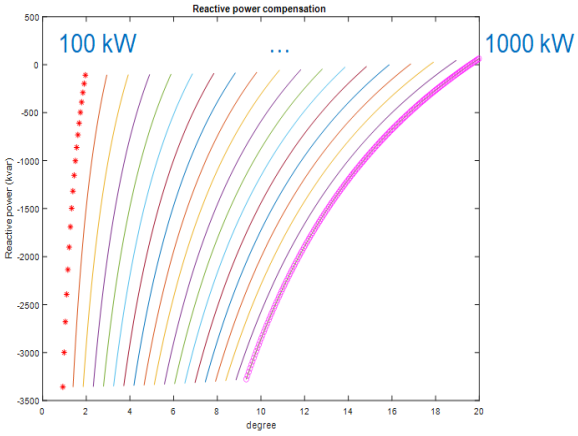


Fig.6. Reactive power limit due to the real power changed

The reactive power compensation capability seems to be highly potential to support var up to around 3400 kvar, independently upon its real power. Unfortunately, this is true just only when X_s = 0.16 W.

3.2. SUT 22-kV power feeder (159 bus system)

A 22-kV electrical distribution system of Suranaree University of Technology (SUT) consisting of 159 electrical buses, Fig. 7,is used as a test system. This system is planned to install a BESS plant in a near future. A PV floating plant was already installed and waiting for a commercial operation date (COD) with the local utility.

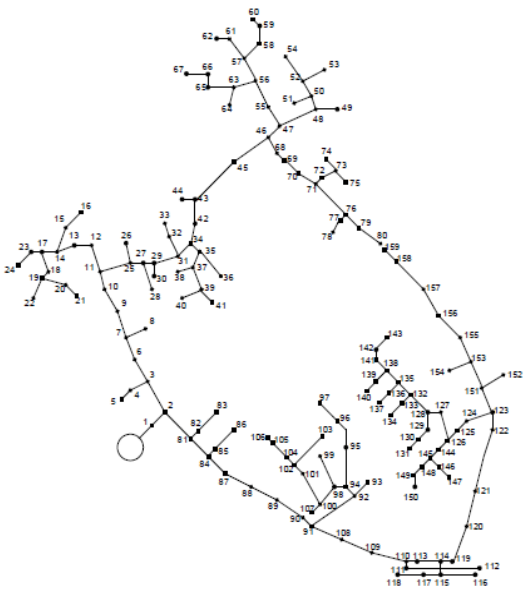


Fig.7. SUT 159-bus test power distribution system

At the point of coupling connection (PCC),assume the transformer rating = 5 MVA, the transformer voltage impedance is fairly 10% of its base value. The transformer reactance, X_T, is 3.2 mW. Transferring the substation short-circuit reactance from 22-kV side to 400-V side, therefore, Z_{SubSC} = 0.106 + j1.06 W.Neglecting the line reactance from the substation to PCC, X_s= 1.063 W. It should note

that X_s at the PCC should be higher than 1.063W. Assume that X_s is varied from 0.01 – 0.5 W while the real power is kept constant at 500 kW. The Impact of equivalent reactance, X_S, is illustrated in Fig. 8.

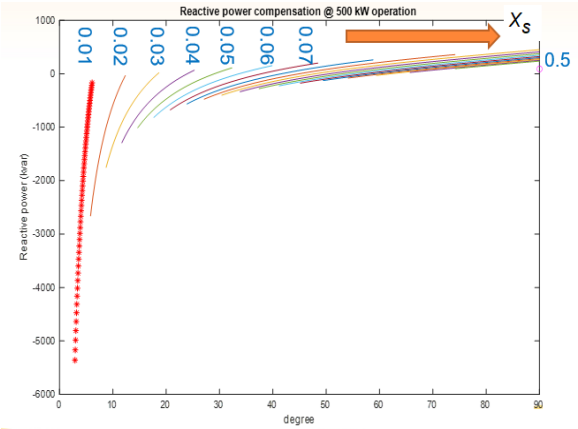


Fig.8. Impact of the equivalent reactance

With an inappropriate reactance, the reactive power is almost constant at each specific real power ($Q_{min} \approx Q_{max}$). The similar results can be obtained at different values of the line voltage magnitude and V_{DC}. To enhance the compensation capability of the BESS, the reactance should be kept as small as possible.Otherwise, an external reactive compensator must be installed to help supporting the system var.

IV. CONCLUSION

The reactive power compensation capacity of a battery storage plant is significantly small. To enlarge the plant reactive power injection needs an external compensator. The key parameter of increasing reactive power compensation is the equivalent source reactance. The value of 0.01 W at the point of coupling connection can have the maximum reactive power limit up to nearly 5 Mvar. In this study, a typical battery plant was investigated. The result showed that -500 kvar is consumed by the plant and this value is almost fixed.

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REFERENCES

[1] F. Islam, K. Prakash, K.A. Mamun, A., Lallu, and H.R. Pota, "Aromatic network: A novel structure for power distribution system", IEEE Access 5, pp. 25236–25257, 2017

[2] F. Islam, K. Prakash, K. Mamun, A. Lallu, and R.R. Mudliar,"Design a optimum MPPT controller for solar energy system", Indonesian J. Electr. Eng. Comput. Sci. 2,pp. 545-553, 2016

[3] Y. Wang, N. Zhang, C. Kang, M. Miao, R. Shi, and Q. Xia, "An efficient approach to power system uncertainty analysis with high-dimensional dependencies", IEEE Trans. Power Syst. 33, pp. 2984–2994, 2017

[4] A.M. Nour, A. Y. Hatata, A. A. Helal, and M.M. El-Saadawi, "Review on voltage-violation mitigation techniques of distribution networks with distributed rooftop pv systems", IET Gener. Transm. &amp. Distrib. 14, pp. 349–361, 2019

[5] G.C. Kryonidis, E.O. Kontis, T.A. Papadopoulos, K.D. Pippi, A.I. Nousdilis, and G.A. Barzegkar-Ntovom, "Ancillary services in active distribution networks: A review of technological trends from operational and online analysis perspective", Renew. Sustain. Energy Rev. 147, 2021

[6] Y.H. Song, and A.T. Johns, "Flexible AC transmission systems (FACTS)", The Institution of Electrical Engineers, London, UK, 1999.

[7] C.R.C. Lima, J.M. Guilemany, "Adhesion improvements of Thermal Barrier Coatings with HVOF thermally sprayed bond coats", Surface and Coatings Technology, vol.201,no.8,pp.4694–4701,15 January 2007,.

[8] Esfahanian, A. Javaheri, and M. Ghaffarpour, "Thermal analysis of an SI engine piston using different combustion boundary condition treatments", Applied Thermal Engineering,vol.26,pEsfahanian, A. Javaheri, and M. Ghaffarpour, "Thermal analysis of an SI engine piston using different combustion boundary condition treatments", Applied Thermal Engineering,vol.26,pp.277-287,2006.", Surface and Coatings Technology,vol. 203, pp. 91-98, 2008.

[9] Anna Gilbert,Esfahanian, A. Javaheri, and M. Ghaffarpour, "Thermal analysis of an SI engine piston using different combustion boundary condition treatments", Applied Thermal Engineering,vol.26,pp.277-287,2006., Surface and Coatings Technology,vol..202,pp.2152-2161,2008.

[10] T. Hejwowski, and A. Weronski, "The effect of thermal barrier coatings on diesel engine performance", Vacuum,vol.65, pp.427-432, 2002.

[11] E. Buyukkaya, "Thermal analysis of functionally graded coating Al-Si alloy and steel pistons", Surface and Coatings Technology,vol.202,pp. 3856-3865, 2008.

[12] E. Esfahanian, A. Javaheri, and M. Ghaffarpour, "Thermal analysis of an SI engine piston using different combustion boundary condition treatments", Applied Thermal Engineering,vol.26,pp.277-287,2006.,pp.398-402,2007.

[13] M. Cerit, V. Ayhan, A. Parlak, and H. Yasar, "Thermal analysis of a partially ceramic coated piston: Effect on cold start HC emission in a spark ignition engine", Applied Thermal Engineering,vol. 31,no. 2 –3,pp.336-341,2011.

[14] Michael Anderson Marr, "An Investigation of Metal and Ceramic Thermal Barrier Coatings in a Spark-Ignition Engine", M.S thesis, Mechanical and Industrial Engineering, University of Toronto, 2009.

[15] V. Esfahanian, A. Javaheri, and M. Ghaffarpour, "Thermal analysis of an SI engine piston using different combustion boundary condition treatments", Applied Thermal Engineering,vol.26,pp.277-287,2006.

[16] Muhammet Cerit, "Thermo mechanical analysis of a partially ceramic coated piston used in an SI engine", Surface & Coatings Technology,vol.205,pp.3499-3505,2011.

[17] Daniel W Parker, "Thermal barrier coatings for gas turbines, automotive engines and diesel equipment", Materials & Design, Vol. 13,no. 6,pp. 345-351,1992.

[18] H. Jamali, R. Mozafarinia, R. Shoja Razavi, and R. Ahmadi-Pidani, "Fabrication and Evaluation of Plasma-Sprayed Nanostructured and Conventional YSZ Thermal Barrier Coatings", Ceramic International,vol.38, pp.6805-6712,2012.

[19] R. Ahmadi-Pidani, R. Shoja-Razavi, R. Mozafarinia, and H. Jamali, "Improving the thermal shock resistance of plasma sprayed CYSZ thermal barrier coatings by laser surface modification", Optics and Lasers in Engineering,vol.50,pp.780–786,2012.

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