Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE USA 2012), Raleigh, USA, September 16-20, 2012

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***Abstract*—**
This paper discusses about the reactive power flow calculation in a dual-active-bridge (DAB) following the CP (conservative power) and PQ (instantaneous reactive power) theories. Based on the results from reactive power calculation, the optimal virtual turns ratio is determined so as to draw equal reactive power from the primary and secondary sides of the DAB-transformer. The equal sharing of the reactive power makes the DAB system more efficient. This paper also discusses about the computation of active and reactive power flow based on experimental data. As an example, a three winding transformer is selected for the experimentation and the better turns ratio is pointed out which can provide better efficiency.

I. Introduction

The basic three-phase Dual-Active-Bridge (DAB) converter configuration is shown in Fig. 1. [1], [2], [3] discuss the working principle of such converters. The DAB converter consists of two three-phase two-level converters and a three-phase high frequency transformer. The three-phase transformer is in star-star configuration with neutral point connected to the DC-bus mid point. The two active bridges can be operated in such a way that they have the same switching frequency and the secondary bridge switches t_ϕ micro-second after the primary one. There are many different topologies proposed by researchers for the DAB. The wave shape of the terminal voltage applied to the three-phase transformer depends on the DAB converter topology. For example, square wave voltages are applied to the transformer primary for the topology shown in Fig. 1. The voltage and current harmonics present can also transfer power along with the fundamental components. If these harmonics increase the transmitted power more than they increase the reactive power, the conduction losses for a certain active power are reduced. Here, it is assumed that the conduction losses give the major contribution to the total losses for the desired operating conditions. The other losses, namely the switching and core losses are intentionally omitted. Therefore, the conduction losses must be reduced in order to achieve higher system efficiencies. Thus, by computing the reactive powers the optimal virtual transformer turns ratio is decided for a given transformer configuration (i.e., start-star or delta-delta winding). The value of leakage inductance can then be determined in order to reach a certain active power flow. In this paper the well-known PQ theory [4] is used to compute the reactive power flow.

In the following paragraphs it is assumed that the magnetizing inductance is much higher than the leakage inductance and therefore it can be neglected. The analysis in this paper has been carried out for a positive active power flow (Fig. 1) from the primary to the secondary side. However, the presented concept is as well valid for an inverse power flow.

In Section II, the framework for calculating the reactive power in a dual-active-bridge is exposed. Two different computation methods namely the CP and PQ methods are presented in this section. A comparative study is carried out between these two methods in section III. Section IV deals with the optimal virtual turns ratio of the transformer for efficient power transfer. Section V concludes the paper.

II. Reactive Power Calculation for a Dual-Active-Bridge Converter

Several theories have been proposed to calculate the reactive power in a system with non-sinusoidal voltages and currents. Among these four major theories are (i) Budeanu's power theory, (ii) FBD theory,

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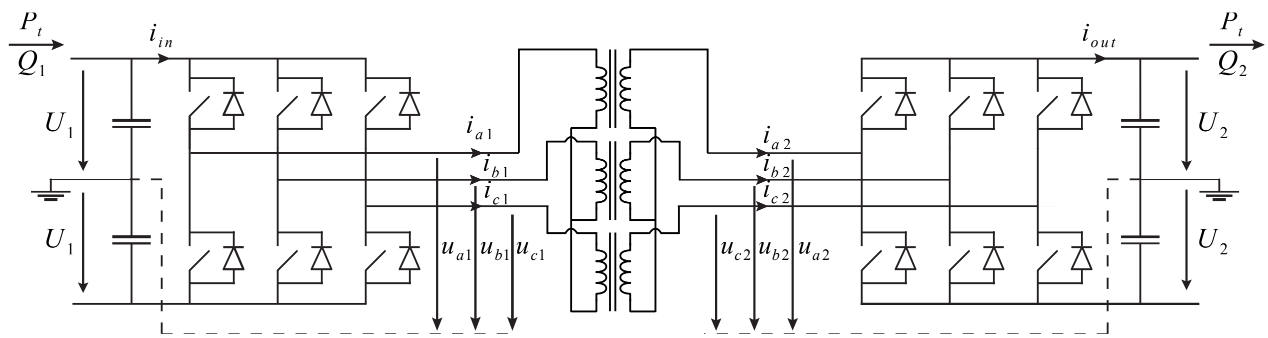


Figure 1: Three-phase dual-active-bridge DC-DC converter

(iii) CP theory and (iv) the pq theory. These theories are summarized and compared in [5] [6]. In this paper, the CP and the PQ theories are considered as suitable and are used to compute the reactive power flow in the DAB converter.

A. CP Theory

It is well known that the active power P_t is defined as the average value over one period as shown below,

$$P_t = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T u(t).i(t)dt$$

where $u(t)$ and $i(t)$ can be scalars or vectors.

This principle is used to compute the reactive power. The method introduces homo-variables of the voltage and the current. Homo-voltages and currents fulfil Kirchhoff's Laws and are thus conservative. This allows to calculate the reactive power as,

$$Q_{cpt} = \frac{1}{T}\int_0^T \hat{u}(t).i(t)dt$$

where, $\hat{u}(t)$ is the homo-integral of the voltage given by $u(t) = \omega_s(u_\int(t) - \bar{U}_\int)$ Here, $\omega_s = \frac{2\pi}{T}$, $u_\int(t) = \int_0^t u(\tau)d\tau$ and $\bar{U}_\int$ is its average value.

B. PQ Theory

The pq theory analyses the instantaneous powers in an orthogonal reference frame (α, β, 0), which is obtained by Clark Transformation from the original (a, b, c) frame. This reference frame transformation is done using the following relation.

$$\begin{pmatrix} x_0 \\ x_\alpha \\ x_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} x_a \\ x_b \\ x_c \end{pmatrix}$$

where x can be the instantaneous value of voltage or current.

The inverse transformation is,

$$\begin{pmatrix} x_a \\ x_b \\ x_c \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} x_0 \\ x_\alpha \\ x_\beta \end{pmatrix}$$

In the orthogonal reference frame, the power parts of p(t) belonging to active, reactive and zero-sequence power can clearly be separated and are given by

$$\begin{aligned} p(t) &= u_\alpha i_\alpha + u_\beta i_\beta + u_0 i_0 = P + \widetilde{p}(t) + P_0 + \widetilde{p}_0(t) \\ &= P_t + \widetilde{p}_t(t) \end{aligned}$$

and

$$q(t) = u_\beta i_\alpha - u_\alpha i_\beta = Q_{pq} + \widetilde{q}_{pq}(t)$$

In the above power equations, P, P_0, P_t and Q_{pq} denote DC quantities and $\widetilde{p}(t)$, $\widetilde{p}_0(t)$, $\widetilde{p}_t(t)$ and $\widetilde{q}_{pq}(t)$ are AC quantities having an average of zero over one period T_s. Thus, the following two equations hold good [5].

$$P_t = \frac{1}{T}\int_0^T p(t)dt$$

and

$$Q_{pq} = \frac{1}{T}\int_0^T q(t)dt$$

III. Comparison Between CP and PQ Theory

The reactive powers drawn from both sides of the converter are calculated using the CP and PQ theories. In this case an experiment is conducted on a 1 : 1 transformer (details are given in Appendix) to compare the results obtained using CP and PQ theories. Fig. 2 shows the experimental results of the reactive powers calculated using CP and PQ methods respectively. Here, Q_1 and Q_2 are the reactive powers drawn from the left and right sides of the DAB converter respectively and the net reactive power drawn by the transformer is indicated as Q_L. Looking at the figure, one can say that the reactive powers calculated with the CP approach differs slightly from the one computed with PQ method. However, it can also be noted that the reactive power calculated using the CP method is always greater than the one using PQ method. The point which goes against the use of PQ method is that it is only applicable in three phase systems, whereas the CP method can be used in single phase systems as well.

The DAB model is also simulated in MATLAB to do a comparetive study between the CPT and PQ methods for calculating the reactive power flow. Fig. 3 shows the simulated results of the reactive powers computed using the CP and PQ methods. Similar to the experimental result (Fig. 2), Q_1 and Q_2 are the reactive powers drawn from the left and right sides of the DAB respectively and Q_L is the net reactive power drawn by the transformer. As it is discussed earlier, the reactive power from CPT method is more compared to the one from PQ method. Fig. 4 shows the ratio of Q_{cpt} and Q_{pq} over the phase shift angle for different ratio of input voltages. The DC voltage U_1 is varied from $500-1200V$ and U_2 is varied from $0V$ to $700V$. The maximal ratio is reached at $\phi \approx 33^0$ for $U_1 = 800V$ as well as $U_2 = 700V$ and the value of the ratio is 1.1.

IV. Optimal Virtual Transformer Turns Ratio

The virtual turns ratio n_p of the transformer is a free design parameter. If the stray-factor in the secondary side σ_2 is small, it corresponds approximately to the physical turns ratio i.e., $\frac{N_1}{N_2}$. The idea is to compute the ratio $\frac{P_t}{Q_{pq}}$ between the transmitted active and reactive power for different n_p over the phase shift angle. A higher $\frac{P_t}{Q_{pq}}$ factor means that more active power can flow for the same reactive power. In other words, the reactive power flow is reduced for the same active power. Thus, the system efficiency is improved in the case of a high $\frac{P_t}{Q_{pq}}$ factor. The reactive power can be calculated in different ways proposed by researchers. In this paper the PQ theory is used to calculate the reactive power demand of the DAB for different turns ratio over the phase shift angle. Fig. 5 shows the $\frac{P_t}{Q_{pq}}$ curves for square-wave voltages.

It is very clear from the figure (Fig. 5) that the ratio between active and reactive power is increasing with a higher value of turns ratio n_p. If $n_p = \frac{U_1}{U_2}$ is selected, then the $\frac{P_t}{Q}$ factor is an envelope indicating the highest ratio between the activeand reactive power for every phase-shift angle. The analytical reason behind this is given below.

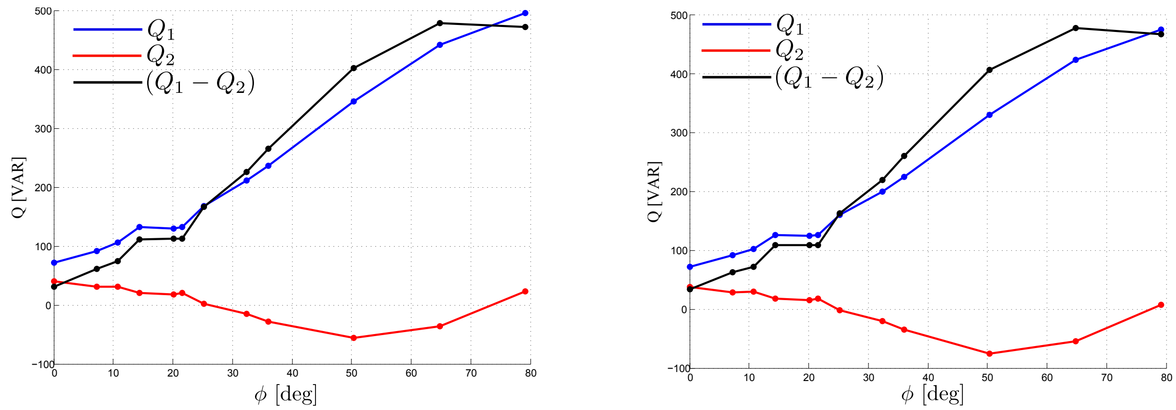
The conduction losses on both sides of the transformer are proportional to the magnitude of the apparent power squared. Thus, it is beneficial to have the smallest possible sum of apparent power magnitudes squared, i.e., $S_1^2 + S_2^2$. The reactive power delivered by the primary and secondary sides can be expressed as a function of the reactive power demand of the DAB system. This is as shown below.

$$Q_1 = xQ; Q_2 = (x-1)Q$$

where, Q_1 and Q_2 are the reactive power delivered from side 1 and side 2 respectively and Q is the reactive power demand of the DAB. The total apparent power can be expressed as,

$$\widetilde{S}_{total} = S_1^2 + S_2^2 = 2P_t^2 + Q^2\{x^2 + (x-1)^2\}$$

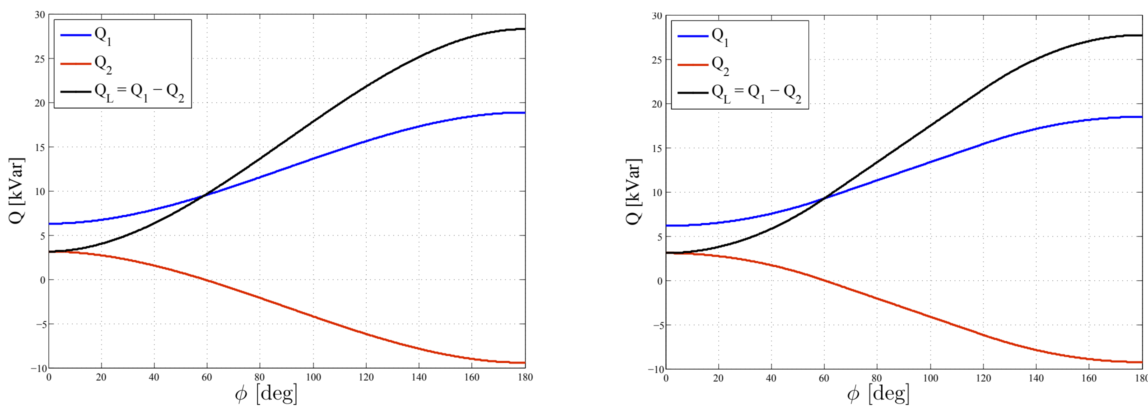
The above expression of total power is minimum for $x = 1/2$. This means that an equal sharing of reactive power from both the converter sides of the DAB



(a) Using CP method (experimental)

(b) Using PQ method (experimental)

Figure 2: Experimental results of reactive powers calculated with the CP and PQ methods over the phase shift angle ϕ



(a) Using CP method (simulated)

(b) Using PQ method (simulated)

Figure 3: Simulated results of reactive powers calculated with the CP and PQ methods over the phase shift angle ϕ

makes the conduction losses minimum. The equal reactive power sharing is possible if the turns ratio of the transformer $n_p = U_1/U_2$. If this virtual turns ratio is not reached then one side of the transformer needs to provide more reactive power. This results in higher total conduction losses. In a system with lot of input and output voltage variations, it is beneficial to choose n_p corresponding to the ratio of averaged input and output voltages.

An experiment is carried out on an existing three winding transformer to select the better winding pair on the basis of P/Q plot. In other words, a winding pair of the three winding transformer is selected which makes the DAB system more efficient. In this case a three winding transformer with turns ratio $1:1:\sqrt{3}$ is selected for the experimentation and from the results the better pair of windings are selected. The initial part of the experiment is carried out between the first and second windings that is for $1:1$ turns ratio (the third winding is left unconnected). Similarly, the later part of the experiment is conducted with the first and third windings, i.e., for $1:\sqrt{3}$ turns ratio. The instantaneous active and reactive powers are computed in the $\alpha-\beta$ reference frame for both the converter sides and for both the cases. These instantaneous powers are stored for a single operating cycle of the DAB and then the average of each active and reactive powers are

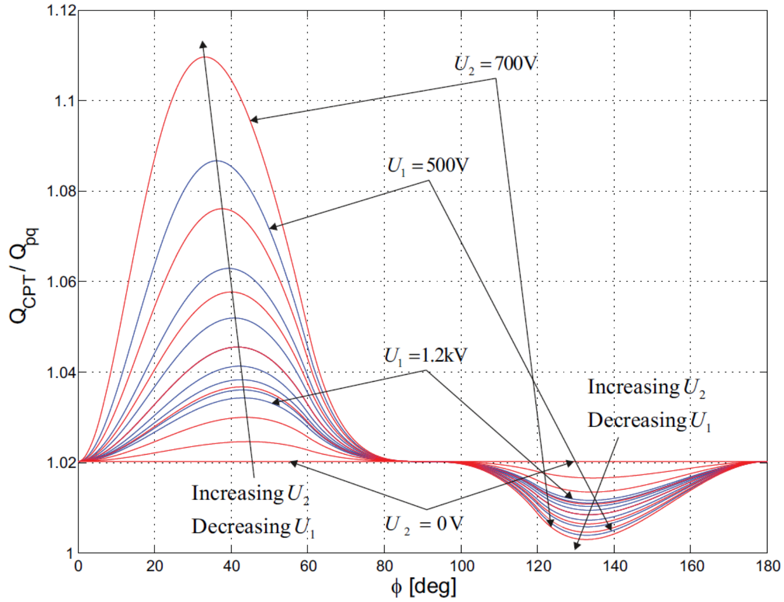


Figure 4: The ratio of Q_{cpt} and Q_{pq} over the phase shift angle for different ratio of input voltages

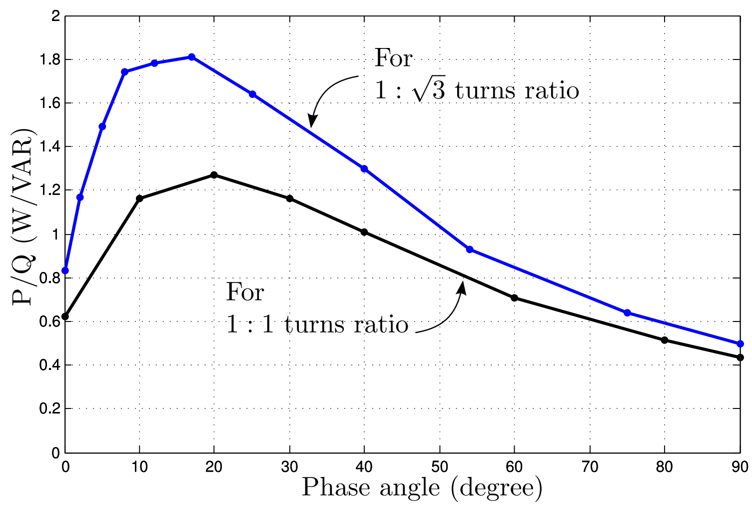


Figure 5: Ratio P_t/Q_1 for different turns ratios over the phase shift angle ϕ (from experimental data)

noted down. Next, the net active power flow from one side of the DAB converter to the other side for one operating cycle of the DAB is also noted down. Similarly, the reactive power consumed by the transformer is also computed. The variation of P/Q with respect to the phase angle for the two turns ratios are shown in Fig. 5. Looking at this plot, one can easily identify that the turns ratio $1 : \sqrt{3}$ provides maximum efficiency compared to the other one.

The figure also shows the simulated waveform with $1 : \sqrt{3}$ turns ratio. This is to show that the shape of the experimental curve matches with the simulated one. However, simulated curve tells about higher value of active power transfer compared to the experimental one. This is due to the looses associated with the practical transformer.

V. Conclusion

In this paper the CP and PQ theories are discussed and applied to the dual active bridge converter in

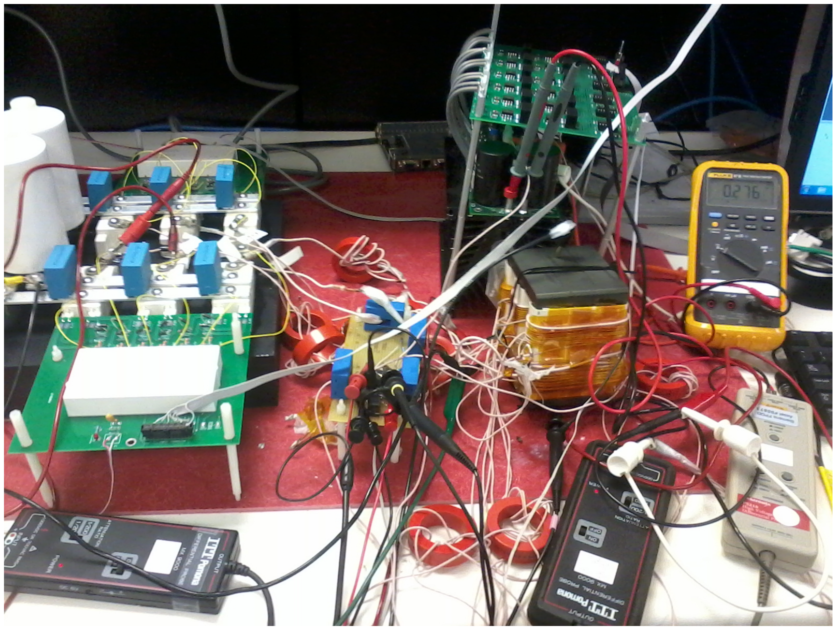


Figure 6: Photo of the experimental DAB setup

order to calculate the reactive power flow. For the computations it was assumed that the magnetizing inductance is much higher than the leakage one and hence it can be neglected. Following the pq framework, the P_t/Q_1 factor is computed for different virtual turns ratios in order to determine the optimal value of the ratio. This optimal value of turns ratio gives best possible efficiency of the dual active bridge converter. Here it is shown that $n_p = U_1/U_2$ results in lowest total reactive power demand and hence small conduction losses. This is dueto the fact that in this case the reactive power is fed equally from both the converter sides. This demand is for the leakage inductance only as the magnetizing inductance is neglected.

An experiment is also conducted on an existing transformer to select a turns ratio from a set of two which provides maximum efficiency. The selected transformer has three windings with $1:1:\sqrt{3}$ as the turns ratio. From the experimental data, the active power flow and the reactive power consumed are computed and the ratio of P and Q is plotted with respect to the phase angle ϕ. Looking at this plot, one can easily select the turns ratio which provides maximum power transfer and hence maximum efficiency.

VI. Appendix

The specifications of the experimental setup are as given below.

Power rating: $1kVA$, Voltage rating (rms) : $400V$, DC bus voltage of the DAB converter: $200V$

VII. Acknowledgement

The authors would like to acknowledge ARPA-E for funding the Project. The authors are also grateful to FREEDM Systems Center for sharing the common lab resources. This work was supported by ERC Program of the U.S. National Science Foundation under Award Number EEC-08212121.

References

[1] G. D. Demetriades and H. Nee, “Dynamic modelling of the dual-active bridge topology for high-power applications,” in *IEEE Power Electronics Specialists Conference*, 2008, pp. 457–464.

[2] R. W. D. Doncker, D. M. Divan, and M. H. Kheraluwala, “A three-phase soft-switched high power density dc/dc converter for high power applications,” in *IEEE Industry Applications Society Annual Meeting*, vol. 1, Oct 1988, pp. 796–805.

[3] M. H. Kheraluwala, R. W. Gascoigne, D. M. Divan, and E. D. Baumann, “Performance characterization of a high-power dual active bridge dc-to-dc converter,” *IEEE Tranactions on Industry Applications*, vol. 28, pp. 1294–1301, 1992.

[4] H. Akagi, E. H. Watanabe, and M. Aredes, “Instantaneous power theory and applications to power conditioning,” in *IEEE Press Series on Power Engineering*. Wiley-Interscience, New Jersey (USA), 2007, p. 338.

[5] H. Paredes, F. Marafao, and L. da Silva, “A comparative analysis of fbd, pq and cpt current decompositions- part i: Three-phase three-wire systems,” in *Power Tech, 2009 IEEE Bucharest*, 2009, pp. 1–8.
[6] F. Marafao, H. Paredes, and L. da Silva, “A comparative analysis of fbd, pq and cpt current decompositions- part ii: Three-phase four-wire systems,” in *Power Tech, 2009 IEEE Bucharest*, 2009, pp. 1–6.