International Conference on Renewable Energies and Power Quality (ICREPQ'16)
Madrid (Spain), 4th to 6th May, 2016
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.14 May 2016

Development and Implementation of an Autotransformer Fasor Controller in Zigzag (ADZ) on ATPDraw Software 4.0

M. Antonio Eduardo Ceolin[1], M. Walkyria Krysthie Arruda Gonçalves[2], M. Ronan Marcelo[3], M. Tais[2] , R. Machsuel Francisco[2] , K. Guilherme Yuji[2]

[1] University of São Paulo (USP)
São Carlos, SP (Brazil)
Phone/Fax number:+55 65 81264065, e-mail: antonio.momesso@usp.br

[2] Department of Electrical Engineering
Federal University of Mato Grosso
Campus of Cuiabá – Cuiaba, MT (Brazil)
Phone/Fax number:+55 65 36271115, e-mail: walkyria@ufmt.br, taismartins.ene@gmail.com, machsuel@outlook.com, guilhermeyujikume@hotmail.com

[2] Electrical and Electronic Department of the IFMT
Campus of Cuiabá – Cuiaba, MT (Brazil)
Phone/Fax number:+55 84061663, e-mail: **ronan.martins@cba.ifmt.edu.br**

Abstract. This paper aims to present the performance of a computationally implemented model of a special autotransformer called ADZ [1]. This zigzag autotransformer allows mitigating the harmonic content produced by power converters as well as varying the power flow by means of controlling voltage phasors. Thus, due to its principle of operation that will be addressed here, ADZ can be considered as a FACTS device in dealing with power quality problems. Furthermore, the steps to the implementation of the model in the well-known ATPDraw (Alternative Transient Program), which can be followed so as to create other templates, will be summarized. Finally, the performance analysisof the implemented model are made through case studies.

Key Word

FACTS, ADZ, ATP, Phase Shifter Transformers.

1. Introduction

The ever-increasing interconnections of power systems lead to a predominance of meshed networks over the radial topologies. Despite increasing the system reliability, there is consensus that in meshed networks some lines are underutilized whereas others can operate in overload conditions [2]. In recent years, however, factors such as cost and environmental impact have delayed the constructions of new sources of electricity and this scenario has required a reassessment of the concepts and practices in power systems, in order to achieve greater flexibility and better use of existing structures. Therefore, the concepts of flexible transmission systems or FACTS have been put forward, which have been widely applied by using a great diversity of equipment such as the well-known Phase-Shifters which are transformers designed to control the voltage module and phase-angle.

Another point that is well established is the set of advantages of the autotransformers [3] over the conventional transformers of the same rating if the transformation ratio is around ±10%, such as their lower cost and reduced losses that leads to a higher efficiency [4], [5], [6], [7].

In order to gather the advantages of autotransformers and the versatility of the zigzag connection ([8], [9], [10] and [5]), a special zigzag autotransformer (ADZ) was created and implemented by [11]. It has been applied to 24-pulse converters, widely used in arc furnaces and HVDC transmission systems ([11], [12], [13] and [14]), as well as to the stabilization of AC power system [15].

In this work, ADZ is applied to control the power flow of a transmission line by means of varying the voltage module and/or phase angle in a specific bus bar. To do so, the model conceived by [11] was implemented at ATPDraw (Alternative Transient Program) through a sequence of steps [1] that is shown in this paper and can be well employed to create similar templates. Eventually, some typical case studies are carried out in order to analyse the performance of the implemented scheme. It is also worth emphasizing that such implemented model can be used in other application such as multi-pulses converters to deal with power quality issues.

2. Principle of operation of ADZ

As mentioned before, the utilization of small transformer ratios autotransformers together with the zigzag connection leads to technical and economic benefits when compared to that conventional ones. Due to this fact, the phase shifter autotransformer ADZ was conceived by [11] and consists of a three-phase set of a main coil (N1) and two auxiliary windings (N2 and N3) per phase. The coils are connected to perform a three-phase autotransformer in which the main windings are in wye connection and linked to the auxiliary ones through zigzag configuration, as shown in Fig. 1.

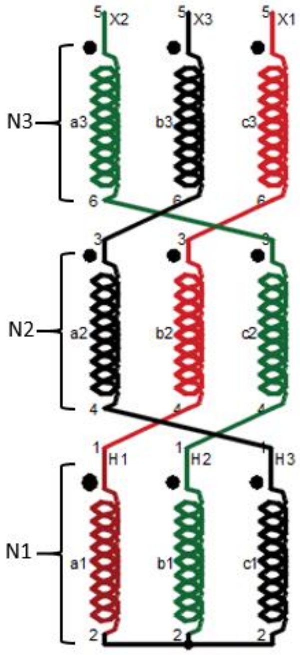

Fig. 1. The ADZ structure

If the input voltage phasors, applied to the main windings a1, b1 and c1, are those shown in (1), (2) and (3), respectively,

$$\dot{U}_{A1A2} = K * N_1 \llcorner 0° \tag{1}$$
$$\dot{U}_{B1B2} = K * N_1 \llcorner -120° \tag{2}$$
$$\dot{U}_{C1C2} = K * N_1 \llcorner 120° \tag{3}$$

where:

$$K = 4{,}44 * \emptyset * f \tag{4}$$

Simultaneously, it is induced in the two series auxiliary coils, the voltages:

$$\dot{U}_{A3A4} = K * N_2 \llcorner 0° \tag{5}$$
$$\dot{U}_{B3B4} = K * N_2 \llcorner -120° \tag{6}$$
$$\dot{U}_{C3C4} = K * N_2 \llcorner 120° \tag{7}$$

and:

$$\dot{U}_{A5A6} = K * N_3 \llcorner 0° \tag{8}$$
$$\dot{U}_{B5B6} = K * N_3 \llcorner -120° \tag{9}$$
$$\dot{U}_{C5C6} = K * N_3 \llcorner 120° \tag{10}$$

Thus, from Figure 1, the voltage in phase A is given by:

$$\dot{U}_{C5A2} = \dot{U}_{A1A2} + \dot{U}_{B3B4} + \dot{U}_{C5C6} \tag{11}$$
$$\dot{U}_{C5A2} = K * N_1 \llcorner 0° + K * N_2 \llcorner -120° + K * N_3 \llcorner 120° \tag{12}$$

This output voltage phasor may be written in terms or its real and imaginary parts in (13)

$$\dot{U}_{C5A2} = K * N_1 \left[1 - 0{,}5 * \left(\frac{N_2 + N_3}{N_1}\right) + j0{,}866 * \left(\frac{N_3 - N_2}{N_1}\right)\right] \tag{13}$$

or:

$$\dot{U}_{C5A2} = U \llcorner \theta \tag{14}$$

where:

$$U = K * N_1 * (a^2 + b^2)^{1/2} \tag{15}$$

and:

$$\theta = \tan^{-1}\left(\frac{b}{a}\right) \tag{16}$$

where:

$$a = 1 - 0{,}5 * \left(\frac{N_2 + N_3}{N_1}\right) \tag{17}$$

and:

$$b = 0{,}866 * \left(\frac{N_3 - N_2}{N_1}\right) \tag{18}$$

The ratio between the output and the input voltages is given by (19):

$$\frac{\dot{U}_{C5A2}}{\dot{U}_{A1A2}} = \frac{U \llcorner \theta}{K * N_1 \llcorner 0°} \tag{19}$$

So that the output voltage can be written in terms of the input voltage in (20).

$$\dot{U}_{C5A2} = (a^2 + b^2)^{1/2} * \dot{U}_{A1A2} \llcorner \theta \tag{20}$$

Similarly, this can be done for other phases:

$$\dot{U}_{A5B2} = (a^2 + b^2)^{1/2} * \dot{U}_{B1B2} \llcorner \theta \tag{21}$$
$$\dot{U}_{B5C2} = (a^2 + b^2)^{1/2} * \dot{U}_{C1C2} \llcorner \theta \tag{22}$$

Hence, the expressions above show that both the magnitude and the angle of the output voltage phasor depend on the ratios N_2/N_1 e N_3/N_1. Therefore, if N_2=N_3, the output voltage phasor will be in phase with the input voltage phasor.

Moreover, another factor that affects the output voltage is related to the polarities of the auxiliary coils. Thus, the polarity inversion of the auxiliary coil N_3, causes to the following expression:

$$\dot{U}_{C5A2} = K * N_1 \left[1 - 0{,}5 * \left(\frac{N_2 - N_3}{N_1}\right) + j0{,}866 * \left(\frac{-N_3 - N_2}{N_1}\right)\right] \tag{24}$$

By comparing equation (13) to (24), it can be noticed that the polarity inversion just leads to the signal change for N_3. Therefore, in a general way, if there is a polarity inversion of the auxiliary coil there will be a reversal of the associated signal at the equations, which is summarised in Table I with respective phasor diagram in Fig. 2.

Table I – Polarities of the auxiliary coils N_2 and N_3 related to the phasor diagrams in Fig. 2

Figure	Auxiliary Coil N_2	Auxiliary Coil N_3
Fig. 2 (a)	Positive	Positive
Fig. 2 (b)	Positive	Negative
Fig. 2 (c)	Negative	Positive
Fig. 2 (d)	Negative	Negative

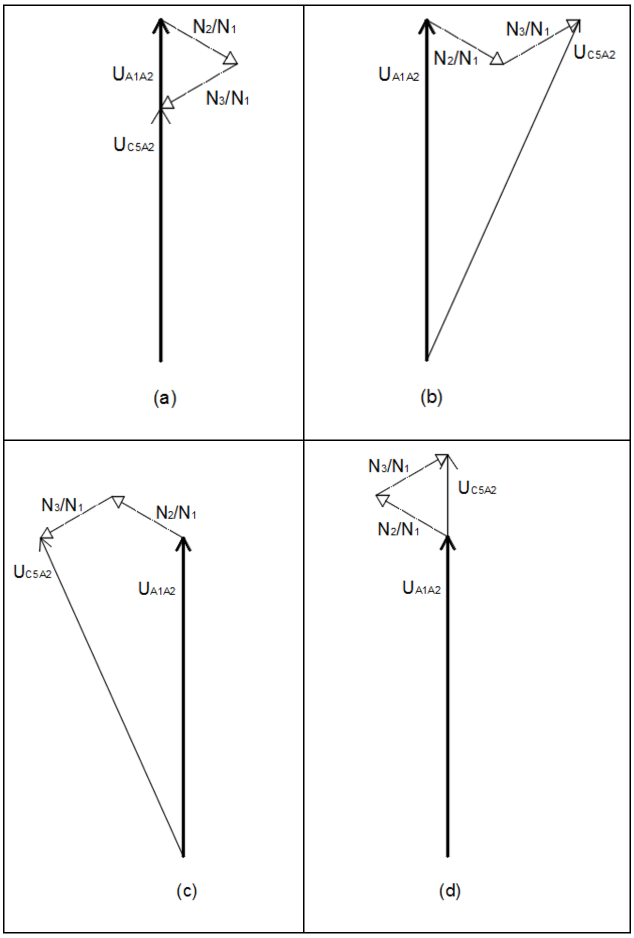

Fig. 2. Phasor diagram related to Table I

3. Computational implementation

The computational implementation of the phase shifter autotransformer ADZ in ATPDraw has been made in two steps which are detailed in the following subsections with subsequent simulations to test its effectiveness.

A. Conception of a single-phase transformer with three independent windings

A special single-phase transformer with three independent windings is required so as to have the connection versatility needed by the complex topology of the ADZ. In this case, one of the windings is used as the main one and the two other are the auxiliary ones. Hence, in order to accomplish that and due to the fact that there is not this type of single-phase transformer in the ATPDraw, a new card named TRAFO_2_BOBINA.LIB, type Data Base Module (DBM), has been created from an existing transformer called “Saturable 1 phase”. The archive thus obtained constitutes the basis of the new component (TRAFO_2_BOBINA.SUP) now available by the ATPDraw. Further information about these procedures can be found in reference [1].

At this point, it is suitable to show the effectiveness of the new single-phase transformer when three of them are connected as a bank to work as a delta/zigzag three-phase transformer. Fig. 3 shows that the main coils are connected in delta and the auxiliary ones are in zigzag configuration.

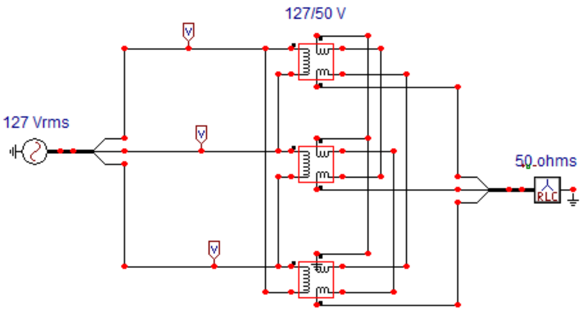

Fig. 3. Simulated circuit using a bank of three single-phase transformers in delta/zigzag

This connection has been chosen so as to compare its result to that one obtained from the simulation of a delta/zigzag three-phase transformer that is already available in ATPDraw. Nevertheless such choice, it must be pointed out that it is also possible to simulate wye/zigzag with the original ATPDraw library as well as with the new card developed in this work. Figs. 4 and 5 show the voltage wave forms at the primary and secondary terminals for the simulation of a bank of three single-phase transformers in delta/zigzag connection and a delta/zigzag three-phase transformer, respectively, and it can be promptly seen a very good correlation between them.

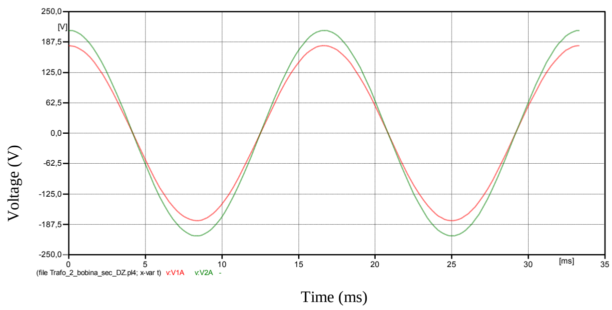

Fig. 4. Voltage wave forms at primary (red) and secondary (green) of a bank of three single-phase transformers in delta/zigzag

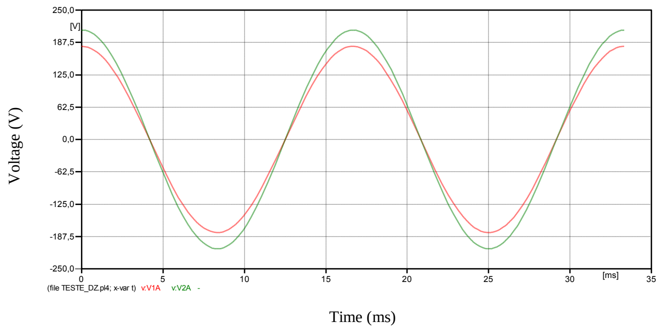

Fig. 5. Voltage wave forms at primary (red) and secondary (green) of a three-phase transformer in delta/zigzag

B. Implementation of the ADZ in ATPDraw

Once the above template has been created and tested in a bank of transformers, the main goal at this step of implementation is to connect the three single-phase transformers with three independent windings in such a way to reach the zigzag autotransformer topology of ADZ, as shown in Fig. 6. In this case, the main coils are in wye configuration and they are also connected to the auxiliary windings to perform the autotransformer according to one of the polarity scheme mentioned in Tab. I and the phasor diagram of which is drawn in Fig. 2(a).

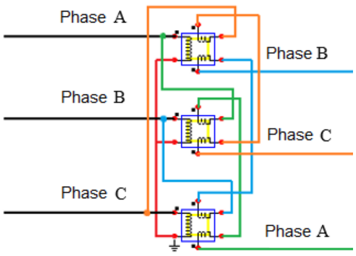

Fig. 6. Connection of the three single-phase transformers with three independent windings as an autotransformer ADZ

Therefore, knowing that the dotted terminals are the positive polarities of each winding and by properly connecting them, it is possible to have the other three configurations listed earlier. Thus, by using the ATPDraw tool called "Compress" [16], the four blocks named ADZ++, ADZ+-, ADZ-+ and ADZ-- have been created (Fig. 7) within which there is one of those four types of connections mentioned in Tab. I, respectively.

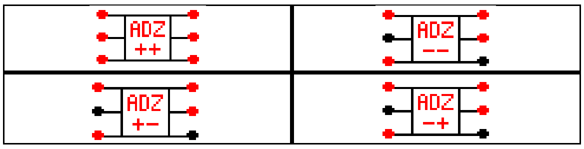

Fig. 7. Blocks created with "Compress" at ATPDraw

In this way, the user will just access the six external terminals of the three-phase equipment and the respective parameters window to input the data for the chosen block, which depends on the operational objectives.

Again, the success of the last implementation is verified through two case studies on the electrical system presented in Fig. 8.

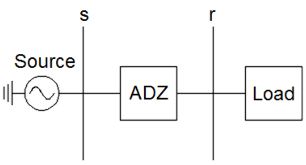

Fig. 8. Connection diagram for simulate cases.

In the first case, the equipment is supposed to not interfere in the system by no change in the magnitude or in the phase-angle of the voltage phasor at the bar "r". This could be the case in which the system is under normal conditions and some control loop make the taps not operate. Moreover, it is worthy to point out that this situation can be simulated by using anyone of the four designed blocks described above. Fig. 9 and 10 present the wave forms and de phasor diagram, respectively, for both primary and secondary ADZ voltages.

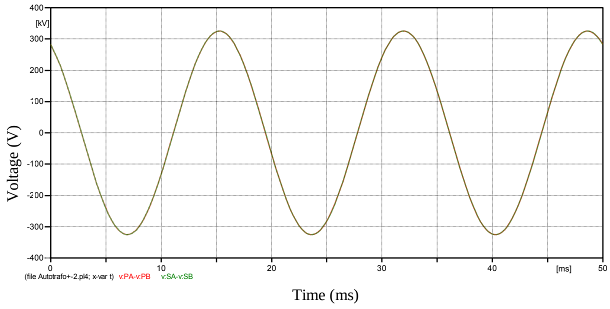

Fig. 9. Voltage wave forms at primary (red) and secondary (green) – Case 1

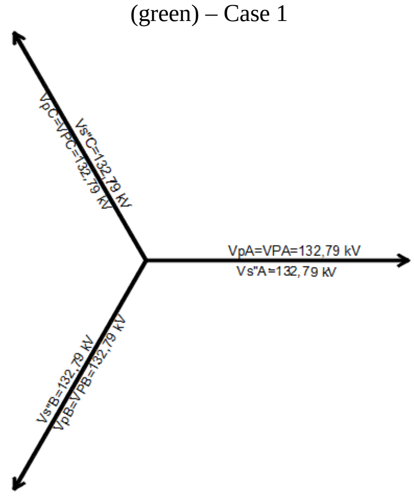

Fig. 10. Phasor Diagram – Case 1

It can be noticed from the figures that the primary and secondary ADZ voltages are in phase and with the same magnitude, as it was expected.

On the other hand, the second case aims to show the performance of the ADZ when it is supposed to act over the secondary voltage module (from 0.85 p.u. to 1 p.u) and phase-angle (where secondary voltage must lead primary voltage by 15º) in order to meet some system requirement.

Through the time domain graph and phasor diagram in Figs. 11 and 12, respectively, it can be promptly seen that the secondary voltage (green line) is bigger and in advance when compared to the primary one (red line), as it was expected again.

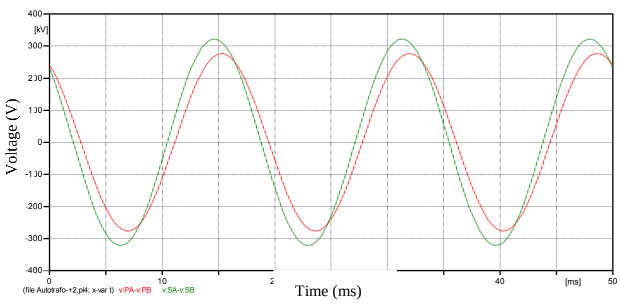

Fig. 11 Voltage wave forms at primary (red) and secondary (green) – Case 2

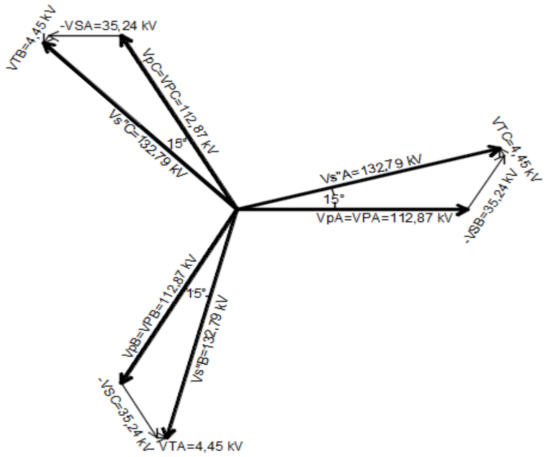

Fig. 12. Phasor Diagram – Case 2

It can also be seen in Fig. 12 the voltage phasors at the auxiliaries coils (VS and VT) that are added to the voltage at the main coil (Vp) to result in the aimed secondary voltage which confirms the implemented model effectiveness.

4. Power System Simulations

To verify the operational performance of the ADZ towards controlling the power flow or offsetting adverse conditions in the power system, some computer simulations have been performed. Fig. 13 ((a) without ADZ and (b)with ADZ) illustrates a single line diagram of the electrical fictitious simulated grid, which consists of a ring portion in an interconnected system. In the bars 1 and 2 the generators are represented by their Thèvenin´s equivalent circuit, which are designated by G_1 in series with ZG_1 and G_2 in series with ZG_2, respectively. The transmission lines TL_1, TL_2 and TL_3 are represented by their impedances which RL parameters can be found in Table II.

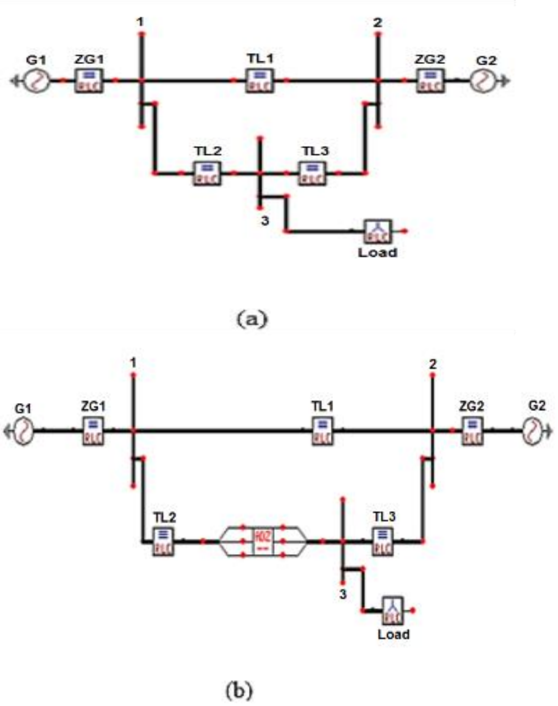

Fig. 13. Single line diagram of the simulated grid: (a) without ADZ; (b) with ADZ.

Table II. – Generators and transmission lines RL parameters

Impedance	Resistence (Ω)	Inductance (mH)
TL1	1	500
TL2	0.5	250
TL3	1	250
ZG_1	0.25	450
ZG_2	0.85	200

Finally, in the bar 3 there is a wye connected load of 100MVA (0.96 lagging power factor) at 230kV.

Firstly, the system depicted above has been simulated so as to know its original condition of power flow and generators loading, without the presence of the ADZ and, therefore, this information can be found in Table III and IV.

Table III – Power flow through the transmission lines without ADZ

TL	Aparent Power (MVA)	Active Power (MW)	Reactive Power (MVAr)
TL1	6.20	5.82	2.14
TL2	37.51	35.97	10.65
TL3	49.61	47.67	13.75

Table IV. – Generators loading without ADZ

Generator	Aparent Power(MVA)	Active Power(MW)	Reactive Power(MVAr)
G1	33.71	30.17	15.03
G2	59.63	53.60	26.14

From Table IV it can be noticed that the total power generated (87.13 MVA) to meet the load demand is not equally distributed between the generators. Thus, considering that this loading balance is a system requirement to be met, the ADZ has been connected between bars 1 and 3 (Fig. 13(b)) in order to control the power flow through the line TL_2. Therefore, by setting the ADZ to act over the secondary voltage phase-angle (5º leading the primary voltage), it was possible to transfer a part of the loading from line TL_3 to line TL_2 and, hence, to balance the generators loading, as can be seen in Tables V and VI.

Table V. - Power flow through the transmission lines with ADZ acting over the voltage phase-angle

Line	Aparent Power (MVA)	Active Power (MW)	Reactive Power(MVAr)
TL1	13.84	13.62	2.45
TL2	50.58	49.83	8.63
TL3	37.03	33.54	15.68

Table VI. - Generators loading with ADZ acting over the voltage phase-angle

Generator	Aparent Power (MVA)	Active Power (MW)	Reactive Power(MVAr)
G1	40.31	36.72	16.64
G2	53.86	47.25	25.85

Despite reaching the balance between the generators, the voltage at the bar 3 remains in 0.93 p.u. and therefore below the lower acceptable limit. Due to this fact, by setting the ADZ to also act over the secondary voltage magnitude, keeping the prior phase-angle setting, it was possible to bring the referred voltage to the 0.98 p.u. The new operational condition thus obtained is summarized in Tables VII e VIII.

Table VII. - Power flow through the transmission lines with ADZ acting over the voltage phase-angle and magnitude

Line	Aparent Power (MVA)	Active Power (MW)	Reactive Power (MVAr)
TL1	21.19	11.87	17.56
TL2	58.65	48.16	33.48
TL3	44.41	43.92	-6.63

Table VIII. - Generators loading with ADZ acting over the voltage phase-angle and magnitude

Generator	Aparent Power (MVA)	Active Power (MW)	Reactive Power (MVAr)
G1	49.32	36.37	33.31
G2	59.95	55.89	21.69

Under a higher voltage magnitude, the power demanded by the load at bar 3 is increased and, as it can be seen from Table VIII, the generators loadings are thus boosted to 107.41MVA (49.32MVA plus 59.95MVA) in a relatively balanced way.

5. Conclusion

This paper presented the use of the phase-shift transformer (ADZ) to control the power flow of an electric power system, ensuring the voltage quality, by means of varying the voltage module and/or phase angle. Thus, the steps for the computational implementation of the ADZ in ATPDraw have been depicted and can be reproduced in order to create other types of special transformers. Besides, the simulations showed a good performance of the implemented model for the main goal of this work but can be used for other purposes as well. Nevertheless, it must be mentioned that a closed control loop is still lacking in the implemented template of the ADZ and, therefore, every set point is manually adjusted which limits some areas of application.

References

[1] Momesso, A. E. C. **Desenvolvimento e Implementação de um Autotransformador Controlador de Fasor em Zigue-Zague (ADZ) no Software ATPDraw 4.0**. 2015. 113 f. Trabalho Final de Curso (Bacharel em Engenharia Elétrica) - Universidade Federal de Mato Grosso, Cuiabá, MT, 2015.

[2] WIRMOND, V. E. **Alocação de TCPST em Sistemas de Transmissão Usando Algoritmos Genéticos e Fluxo de Potência Ótimo**. 2009. 120 f. Dissertação (Mestrado em Engenharia Elétrica) - Universidade Federal do Paraná, Curitiba, PR, 2009.

[3] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 5.356: Transformador de Potência**. Rio de Janeiro, 1993. 59 p.

[4] LABORATÓRIO DE SISTEMAS DE ENERGIA ELÉTRICA - ESCOLA DE ENGENHARIA DE SÃO CARLOS. **Estratégias para Regulação de Tensão em Transformadores com Comutação de TAP**. São Carlos, SP, [20--]. Disponível em: <http://lsee.sel.eesc.usp.br/index.php/artigos/qualidade-da-energia-eletrica/29-estrategias-para-regulacao-de-tensao-em-transformadores-com-comutacao-de-tap>. Acesso em: 24 maio 2015.

[5] CARLOS DE OLIVEIRA, J.; COGO, J. R.; GONÇALVES DE ABREU, J. P. **Transformadores: Teoria e Ensaios**. São Paulo: Edgard Blücher Ltda. São Paulo: Edgard Blücher Ltda, 1984.

[6] KOSOW, I. L. **Máquinas Elétricas e Transformadores**. Tradução de Felipe Luiz Ribeiro Daiello e Percy Antônio Pinto Soares. 4 ed. Porto Alegre, Rio de Janeiro: Globo, 1919. Vol. 1.

[7] NOGUEIRA, D. S.; ALVES, D. P. **Transformadores de Potência - Teoria e Aplicação: Tópicos Essenciais**. 2009. 212 f. Projeto (Bacharelado em Engenharia Elétrica) - Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, 2009.

[8] GUEDES, M. V. **Transformadores: Ligações e Esfasamentos**. Faculdade de Engenharia - Universidade do Porto. 2004.

[9] Winders Jr., J. J. **Power Transformers: Principles and Applications**. New York: Marcel Dekker, Inc., 2002.

[10] GONÇALVES, V. A. **Redução de Harmônicos de Corrente em Retificadores de Múltiplos Pulsos - Generalização das Conexões Diferenciais**. 2006. 183 f. Dissertação (Mestrado em Engenharia Elétrica) - Universidade Estadual Paulista, Ilha Solteira, SP, 2006.

[11] GONÇALVES DE ABREU, J. P. **Desenvolvimento e Implementação de um Transformador com Relação de Transformação Complexa Variável - Phasor Controller**. 1991. 202 f. Tese (Doutorado em Engenharia Elétrica) - Universidade Estadual de Campinas, Campinas, SP, 1991.

[12] PEREIRA, A. L. M.; BELCHIOR, F. N.; GONÇALVES DE ABREU, J. P. **Análise de desempenho do Auto-transformador ADZ através do Software ATP**. In: Seminário Nacional de Produção e Transmissão de Energia Elétrica, XXI, 2011, Florianópolis - SC.

[13] PAULILLO, G.; GUIMARÃES, C. A. M.; GONÇALVES DE ABREU, J. P. **T-ADZ - A Novel Converter Transformer**. IEEE - Instituto de Engenheiros Eletricistas e Eletrônicos, p. 715-719.

[14] PAULILLO, G.; GONÇALVES DE ABREU, J. P. **Power Converters under Voltage Imbalance A Novel Solution**. IEEE - Instituto de Engenheiros Eletricistas e Eletrônicos, Proto, Portugal, 2001.

[15] DE AZEVEDO, H.R.; MARTINS, R.M.; TEIXEIRA, E.P.; NERYS, J.W.L. **Fuzzy Stabilizer For Power System Using A Switched Zigzag Phase Shift Transformer,** IEEE Catalog Number: 95TH8081

[16] APARECIDO DE OLIVEIRA, A.; MANZOLI, A. C. C.; AGNOLETTO, E. J.; JÚNIOR, J. A. C.; LEITE, L. L. QUADROS, R. **Curso de ATPDraw 5.7: Alternative Transient Program.** Cuiabá, MT, 2014.