ANALYSIS OF OLTC CONTROL OF PARALLEL TRANSFORMERS

Íñigo Ferrero Roberto Cimadevilla José Miguel Yarza Iñaki Solaun

ZIV GRID a CG Group Company ZIV R&D UPV

Abstract

This paper describes the behavior of an on-load tap changer (OLTC) control for up to five parallel transformers. The three main different automatisms are taken into account: the reverse reactance method, the master-follower method and the circulating current method.

Different cases are considered based on RTDS simulations and real connections to Intelligent Electronic Devices (IEDs), where one Automatic Voltage Regulator (AVR) device is associated with each transformer and the piece of information shared between the IEDs, digital and analogical signals, is transmitted by IEC 61850 communications (GOOSE messaging). Even though the three automatisms are covered in depth, the tests are going to be focused on the circulating current method.

The AVRs are going to control 45MVA, 138±13x5%/36 kV, YNd11 power transformers being subject to different situations:

1. Two power transformers working in parallel conditions with the same electrical characteristics:
    a. Being supplied by the same source.
    b. Being supplied by different sources.
2. Two power transformers working in parallel conditions with different electrical characteristics
3. Five power transformers working in parallel conditions.
4. Backup power transformers coming into the system when there is a trip in any of the main power transformers.

In all the above mentioned conditions, decisions are taken in each AVR to maintain the busbar voltage at a given setpoint, keeping also constant the load voltage and trying to reduce the circulating current that appears between the parallel transformers. Moreover, the AVR will keep track of the tap position.

This paper will also describe the communication system due to the fact that using IEC 61850 and GOOSE messages requires no wiring between the transformers, which simplifies the installation of the IEDs, the engineering process, the troubleshooting and implies a reduction of cooper wiring.

***Index Terms*-- IEC 61850, GOOSE service, AVR, parallel transformers, master-follower method, circulating current method.**

I. INTRODUCTION

In order to keep the electrical voltage at a constant level along the grid, power transformers are usually equipped with automatic voltage regulators (AVR) operating over On Load Tap Changers (OLTC). In addition, nowadays, and even more in the future, the requirements related to active and reactive power control and also grid dynamic stability are getting stronger. What is more, with increasing decentralized generation, using multiple DERs on a feeder, voltage and reactive power will have to be controlled at several number of points, becoming a challenge to balance voltage and active/reactive power dispatch. Grid automation and management will be developed to face up to these problems, making use of automatons to enhance system stability both on local and transmission level. So AVRs are a very valuable tool to maintain the voltage profiles along the grid, but they have to work in cooperation with other devices also connected to the grid, e.g. capacitor banks or reactors, in order to control properly not only the voltage but also the reactive power flow.

The parallel operation of power transformers is used to provide reliable supply of the electrical energy as well as being a well-known method for maximizing the power system efficiency, flexibility and availability. On the other hand it is an economical way to cover all those things. Another advantage is the fact that, depending on the load, power still can be delivered even when just one of the transformers is running, and paralleling transformers also allows reducing the transformer size and power loss.

This paper describes the application of AVRs for substations with more than one power transformer what involves a more complex control system to coordinate the operations over the OLTCs of parallel transformers.

Conventional solutions to manage the control of parallel transformers, based on hard-wired connections, are complex, expensive and have same limitations concerning the number of power transformers. Nowadays, the conventional approach to face up with these cases is to implement a centralized control mechanism or to equip the AVRs with vendor specific communication protocols to exchange information between them.

This paper presents a solution based on the newest standards and technologies, a completely open solution that enable the use of AVRs from different manufacturers. The article will describe a control system based on IEC 61850 standards that allow the operation of up to five power transformers in parallel. Three alternative methods will be described, the negative reactance method, master-follower method and the circulating current method. Master-follower and circulating current methods require communication between the voltage control functions on the transformers in the parallel group and this paper will be focused in the last one, the circulating current method.

Although the approach is the use of IEC 61850 standards, what is really needed is limited to the GOOSE service. GOOSE service requires an Ethernet network for publication and subscription, but it’s not necessary to deploy any other additional IEC 61850 service, simplifying IEDs acting as AVRs. As a result of this fact, this solution can be used for IEC 61850 SAS and for non-IEC 61850 substations.

II. POWER SYSTEMS AND THEIR NEEDS

Power quality is an important subject for the distribution network companies. They must guarantee the electricity supply fulfilling their customer requirements; this is why voltage regulation takes an important place in electrical distribution engineering.

Voltage must be kept within specified tolerances. The performance of a distribution system and quality of the service provided are not only measured in terms of frequency of interruption but in the maintenance of satisfactory voltage levels at the customers' premises. The utilities must deal with voltage problems which can arise from large and different power system events such as changes in the load and in the load power factor, line or cable outages, dropped generation, capacitor bank activities, heavy power transfers, parallel flows or extreme load demands (high or low).

While AVRs maintain the bus voltage at a given setpoint, keeping also constant the load voltage and trying to reduce the circulating current that appears between the parallel transformers, paralleling transformers will improve the management of the system itself in the following terms:

1) Power system efficiency. Normally an electrical power transformer gives the maximum efficiency at full load, so depending on the amount of load at any time just those transformers which can give the total demand will be running, being able to switch any of them on or off as necessary to fulfill the total demand, being able to work with the maximum efficiency always.

2) Power system availability. Backup parallel transformers can be switched on when an operating transformer is damaged or needs some maintenance work without power interruptions. In those systems with no backup transformers, the other operating parallel transformers could also handle easily the situation.

3) Power system reliability. When any of the operating transformers is tripped due to a fault, the other parallel transformers in the system will share the load and the power supply is not interrupted. If necessary, backup transformers can automatically be switched on, placing them in parallel avoiding that any of the transformers starts working under overload conditions. Moreover, IEC 61850 and particularly GOOSE messages provide a very high level of reliability. GOOSE service includes a repetition mechanism and a communication failure detection mechanism that assure that published data will be received sooner or later, and that the required countermeasures will be adopted as soon as a communication failure is detected to avoid bad operations. And the latest version of IEC 61850 standards provides two options for seamless redundancy protocols, PRP and HSR, both of them described in IEC 62439-3 standard, so for the backup transformer mechanism to place it in parallel automatically when there is a problem in any of the transformers in service, and for the way to share the information for the circulating current or the master slave methods, GOOSE messages can be used.

4) Power system flexibility: Power demand can be modified, increasing or decreasing with the time, so it is better from a business point of view, being able to connect or remove small transformers in parallel than installing a big rated single transformer and replace it later on, when demand changes, by a different one. Here we can also include the economic issue.

III. CONTROL METHODS FOR TRANSFORMERS WORKING IN PARALLEL

i. Master-Follower Method

The scope for the application of the master– follower method is basically limited to power transformers with similar electric characteristics.

Essentially, one AVR is chosen to be master. This AVR controls the busbar voltage following the typical criteria of this automation function, e.g. voltage control with line drop compensation. And the followers "follow" the decisions of master to issue raise and lower commands. To make this master-follower method work, all the followers must be in manual mode, instead of automatic mode, so that the control based on the voltage measurement is disabled.

This method can be implemented in two different ways depending on how the followers act:

- Following the master's current tap. With the information of the master's tap position, the followers operate to reach the same tap position, or another tap position within a range determined by an offset with respect to the master. In this case, the master needs to provide the followers with at least information of its current tap.
- Following the master's commands, not considering their own current tap. In this case, the master needs to send information to the followers about its decisions of issuing raise or lower commands.

This mechanism has some drawbacks. If the master's and followers' tap positions are not the same, or at least harmonized, from the beginning, this undesired situation will remain as long as all these AVR keep working together in the parallel control. And in the case that one AVR disconnects temporarily from the operation to reconnect later, it could happen that it would be operating with a tap position offset after having missed one or more tap change operations.

Typically, when a parallel group is established and one AVR is selected as master, all the followers check their current tap against the master's one. If the tap difference is above an offset, the followers will start issuing raise or lower commands until making the tap difference be within the offset.

The good performance of this method is based a complex feedback system to guarantee that operations executed by each follower AVR are correct. For example, the master has to inform the rest of AVR in the same busbar about its status as master, as well as the followers need to inform the master about their current tap or the success of their commands. A failure in this feedback system can provoke bad operations.

Next some of the most important issues demanding communications between AVR are described:

- Power transformer connection to busbars and busbars topology. This information determines which transformers are connected to which busbar, and which busbars are connected to each other. This information comprises basically circuit breakers' and isolators' statuses. With these data, AVR can consider within their calculations, algorithms and control logics which transformers are in their parallel group. Additionally, if this information is inconsistent (e.g. master not connected to any busbar or connected to more than one busbar), the control automatism should be blocked.

- There are situations that require the exchange of blocking signals. For example, if there is a tap difference between the master and the followers above an offset, or the master transformer is disconnected from its LV busbar, a blocking signal is generated to block the control automatism.

Another case is if the master AVR is blocked by any reason, then the followers simply will not issue any command and will not need this information. However, if any of the followers is blocked, the master AVR needs to know it to block its automatic voltage control.

The main signals exchanged for the master-follower method are listed in the following table:

TABLE I. EXCHANGED SIGNALS FOR THE MASTER-FOLLOWER METHOD

Signal	Explanation
Master in service	Activated by the AVR selected as master. This signal allows blocking automatism if more than one master is selected too.
Blocked status	Activated when AVR is blocked. It's used to block the master if a follower becomes blocked.
Automatism in master-follower mode	Activated when AVR has master-follower method active.
Parallel group 1, 2,...etc.	Information based on circuit breakers' and isolators' statuses, and generated by each AVR.
Disconnected status	Signal generated by each AVR if its transformer is disconnected by opening of its LV circuit breaker.
Automatic mode	Activated by each AVR depending on its automatic or manual mode status.
Raise tap command	Order from the master to the followers to issue a rise tap command.
Lower tap command	Order from the master to the followers to issue a lower tap command.
Current tap position	It's the master's actual tap position. This information is necessary for the followers when they follow the master's tap position, and to check if the tap difference between any follower and the master is out of a determined offset.

ii. Circulating Current Method

Let´s consider the case of two equal transformers connected in parallel without any load, as it is represented in the circuit of figure 1. Z_{T1} and Z_{T2} represent the impedances of both transformers.

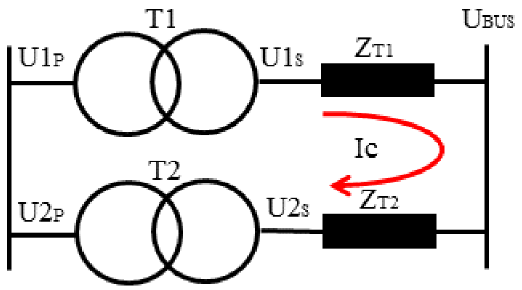

Figure 1. Circuir with two parallel transformers

When both transformers have different tap positions they will have different secondary voltages. This difference will create a circulating current, Ic, between both transformers that can be obtained as:

$$I_{circulating} = \frac{U1_s - U2_s}{Z_{T1} + Z_{T2}} \, (1)$$

If the tap position of transformer T1 is higher than the tap position of transformer T2, U1s will be higher than U2s so there will be circulating current from transformer T1 to transformer T2.

As the X/R ratio of a transformer is very high its impedance can be considered purely inductive, therefore, in formula (1) Z_{T1} and Z_{T2} can be replaced by X_{T1} and X_{T2}. On the other hand, $U1_s$ and $U2_s$ will always be in phase, so its difference $U1_s$-$U2_s$ will also be in phase. That makes the circulating current Ic be always lagging 90º the voltage difference $U1_s$-$U2_s$, so it will be a reactive current.

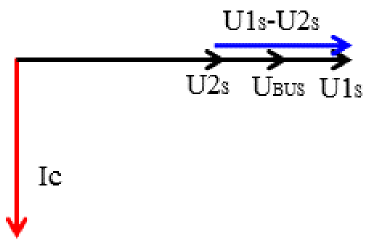

Figure 2. Phasor diagram for the circulating current with regard to the secondary voltages of both transformers

Let´s connect now a load. If we apply the superposition principle, the circulating current will be added to the load current. To analyze this, the circuit of figure 1 will be represented by the equivalent circuit of figure 3. The circuit of figure 4.a, with a load connected, can be decomposed by the superposition principle in two circuits: preload circuit and pure load circuit (figures 4.b and 4.c). The preload circuit will contain the circulating current only and the pure load circuit the load current, once the circulating current is removed.

$$I_{T1} = I_{T1\_preload} + I_{T1\_pure\_load} = I_c + I_{T1\_pure\_load}$$

$$I_{T2} = I_{T2\_preload} + I_{T2\_pure\_load} = I_c + I_{T2\_pure\_load}$$

The circulating current can therefore be obtained by: $I_c = \frac{I_{T1} - I_{T2}}{2}$. As the circulating current is considered purely reactive, the following formula can be applied, in order to avoid vector operations: $I_c = \frac{I_{T1} \times sin\varphi 1 - I_{T2} \times sin\varphi 2}{2}$, where φ1 and φ2 represent the angles between the bus voltage and the currents.

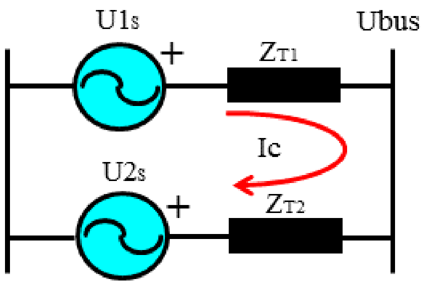

Figure 3. Equivalent circuit of circuit in figure 1.

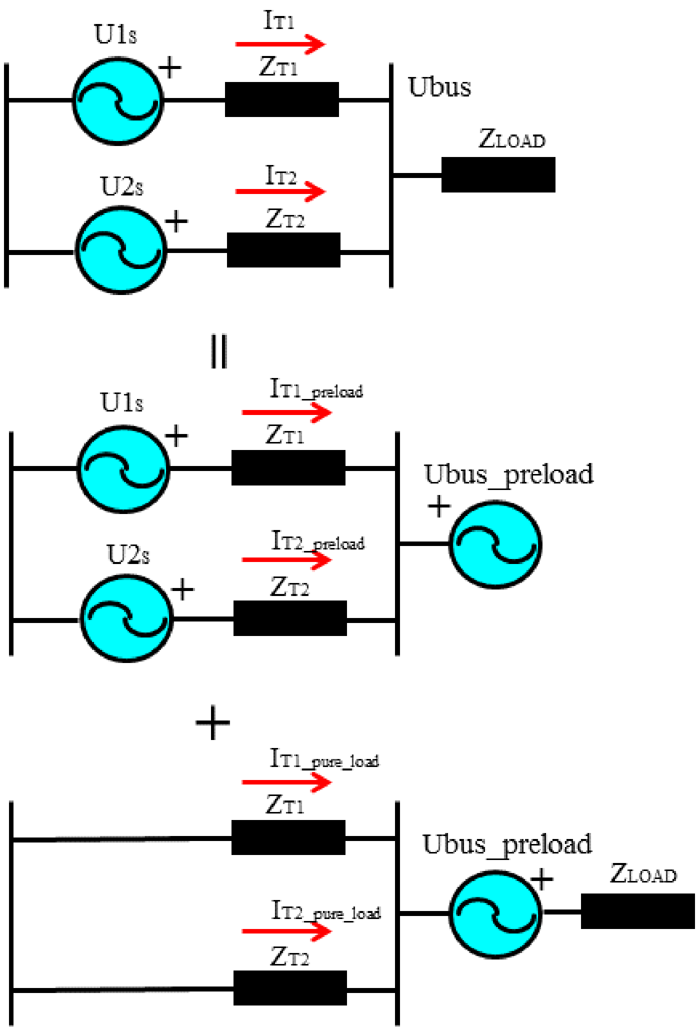

Figure 4. Load circuit (a) decomposed in preload (b) and pure load (c) circuits

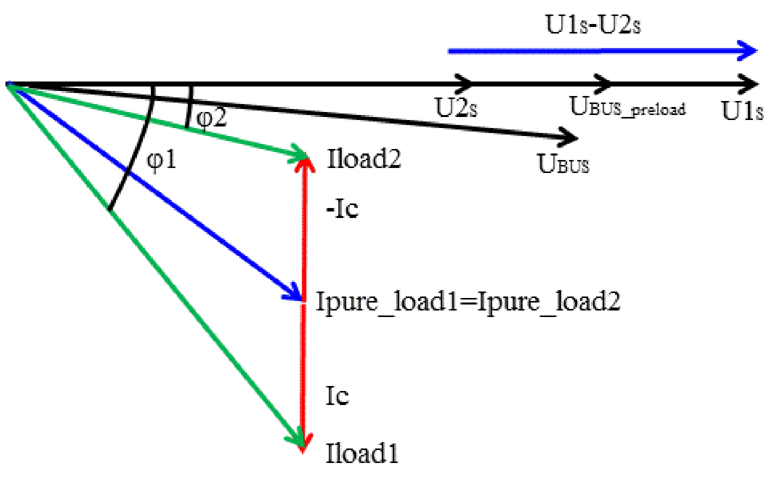

Figure 5. Phasor diagram for the circuit in figure 4

Considering the circuit of figure 3, the circulating current method will try to remove the circulating current making $U1_s=U2_s=$Ubus. As the difference between $U1_s$ and Ubus is equal to $I_c \times Z_{T1}$ and the difference between $U1_s$ and Ubus is equal to $I_c \times Z_{T2}$, the setpoint voltages will be modified as following:

$$V_{COMP1} = V_{CON1} + Z_{T1} \times I_c$$

$$V_{COMP2} = V_{CON2} + Z_{T2} \times I_c$$

The calculated circulating current for transformer T1 will be negative, resulting in a reduction of the setpoint voltage, which will generate a lowering tap command. On the contrary, the calculated circulating current for transformer T2 will be positive, resulting in an increase of the setpoint voltage, generating an increasing tap command.

If the impedances Z_{T1} and Z_{T2} are different, the pure load currents in both transformers will be different and this situation will create a circulating current even if the taps for both transformers are equal. The circulating current method described in this paper tries to minimize the reactive component of the circulating current. Therefore it will adjust the taps to minimize this current. The consequences will be a better reactive power distribution along both power transformers. It is important to use the reactive component of the circulating current as tap changes can only modify the flow of this component but never the flow of the active component.

If each power transformer has an independent source, with different source impedance, the pure load currents in both transformers will also be different resulting in a case similar to the one with different transformer impedances.

As for the master-follower mode, next some of the most important issues demanding communications between AVR are described:

- Power transformer connection to busbars and busbars topology. This information is essential forAVRs operating in the circulating current mode, as this tells them which transformers are in their parallel group. And the automatism will be blocked if any of the transformers is disconnected from the LV busbar (unless it changes to a different operation mode, e.g. hot-standby).

- There are situations that require the exchange of blocking signals. If any of AVR becomes blocked, all the other AVRs working in parallel must also block their operation.
- If one AVR goes to manual mode with the others in automatic mode, those left in automatic must adapt to the manual tapping of the transformer that has been put in manual mode. Each AVR therefore needs to send its control mode status to all other AVR operating in the same parallel group.
- In order to avoid simultaneous tap changes in different transformers, one transformer will be selected to tap first. The AVR that starts a tapping sequence informs the rest of the AVRs to prevent them from starting a tapping sequence until the first AVR completes its own sequence. Once the first AVR concludes the operation, if necessary, the one selected to tap second will follow the same procedure.

The main signals exchanged for the circulating current method are listed in the following table:

TABLE II. EXCHANGED SIGNALS FOR THE CIRCULATING CURRENT METHOD

Signal	Explanation
Blocked status	Activated when AVR is blocked. It's used to block the rest of AVR.
Automatism in circulating current mode	Activated when AVR has this method active.
Parallel group 1, 2,...etc.	Information based on circuit breakers' and isolators' statuses, and generated by each AVR.
Disconnected status	Signal generated by each AVR if its transformer is disconnected by opening of its LV circuit breaker.
Automatic mode	Activated by each AVR depending on its automatic or manual mode status.
Measured transformer current	It's necessary that every AVR have information about currents flowing through all parallel transformers. These measurements need to be known as module-argument or real and imaginary parts, and they can be obtained by communications or by direct measurement through a CT per transformer.
Tapping sequence in course	This signal is activated by each AVR when starts a tapping sequence to avoid simultaneous tap changes in different transformers. To determine the order to tap between AVR, there will be a setting to assign the priority.

iii. Negative Reactance

The negative reactance method uses the line drop compensation method (LDC) with a negative reactance value, being the resistance value equal to zero. The aim of the LDC method is to compensate the voltage drop between the bus and the load (line voltage drop), increasing the bus voltage, in order to keep the load voltage constant. There are two types of LDC methods:

LDC-Z: magnitude compensation, which depends only on the magnitude of the current

LDC-R&X: vector compensation, which depends on the line impedance, current and power factor.

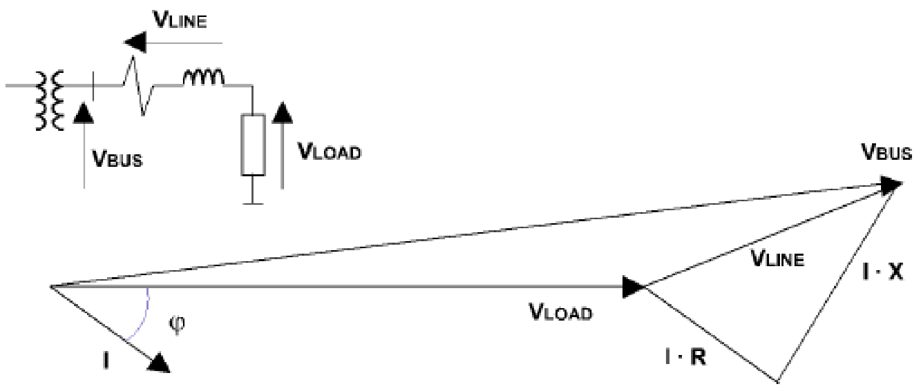

Figure 6. LDC-R&X method

The negative reactance method will use the LDC-R&X taking into account just the voltage drop in the reactance. Figure 7 shows that if a positive X value is used, the bus voltage required will be higher than the load voltage, while if a negative X value is used the bus voltage required will be lower than the load voltage.

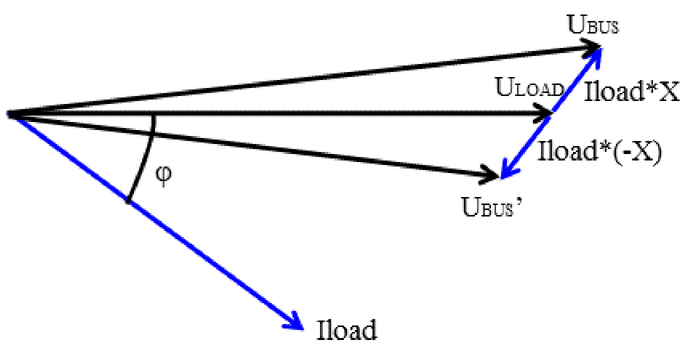

Figure 7. LDC-X with positive and negative values of X

Figure 8 shows the case when a circulating current from T1 to T2 power transformers exists. The circulating current will tend to decrease the magnitude of the current Iload2 and increase the magnitude of the current Iload1. On the other hand it tends to create a phase shift between them. If the voltage drop in the set negative reactance is considered, it can be seen that the required bus voltage for transformer T1 (U_{BUS1}) will be lower than the required bus voltage for transformer T2 (U_{BUS2}). This difference in the required bus voltage or setpoint voltage between both transformers will make that the next tap change will tend to reduce the circulating current.

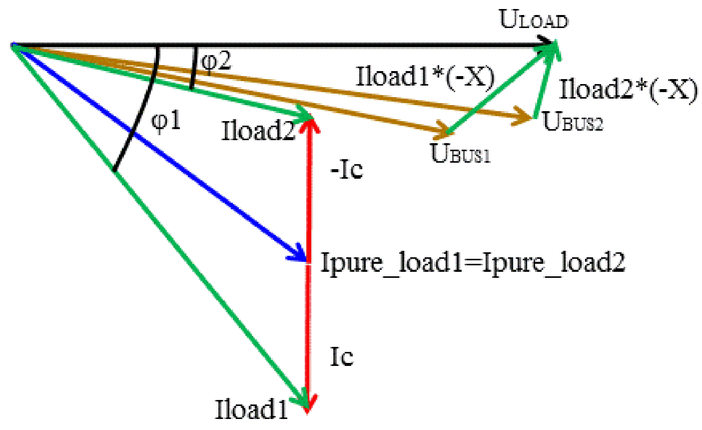

Figure 8. LDC-X using negative values when a circulating current from transformers T1 to T2 exists

IV. TRANSFORMER PARALLELING BASED ON IEC61850

These last years, thanks to the positive development of IEC 61850 inside the substation world, mainly in terms of communication between the bay level and the station level (protection relays, local HMIs, SCADA, etc.), the possibility of a direct communication between the process equipment and even the bay level IEDs has experienced a great boost. In this way, an introduction of a communications channel based on IEC 61850-8-1, would result in benefits for the engineering process, commissioning and future maintenance of the substation environment.

We are not just talking about the reduction of the copper wiring, what at first sight it is automatically translated into cost savings, but also about the reduction of the IEDs size, the automated testing possibilities, taking advantage of the technology, simple wiring and flexible architectures, enhancements of protection functions by giving access to any signal and the well-known interoperability.

Advanced AVR make use of GOOSE service as described in IEC 61850-8-1. It is a multicast service that allows IEC 61850 servers (e.g an IEC 61850 AVR) to communicate information between them. This way, up to five power transformers can be controlled in parallel using the algorithm explained in the following paragraphs.

The big advantages of this system are that a simple ETHERNET network is enough to link every AVR to exchange the information, and that the system is based on an open protocol where different manufacturers' AVR can work together. These advantages involve a big saving in wiring, and an engineering and maintenance simplification by the reduction of wired links. And what is more, this solution is valid for IEC 61850 substation automation systems (SAS) as well as for substations without SAS or based on legacy protocols.

Every AVR will publish a GOOSE message with a dataset and every AVR will subscribe to GOOSE messages published by the others.

The implementation of master-follower method will be done with the exchange of data where different digital signals as well as the tap position are located. Nevertheless, the implementation of circulating current method will be done just sharing the measured transformer reactive power.

Starting with ICD/CID files of AVR, the first step to use GOOSE messages is the creation of a dataset with all data required by AVR to perform master-follower method and circulating current method. The structure of this dataset will be identical for all AVR, and the content will be the information published by each AVR. However, the content of the data set could vary from one substation to another, especially in the case of having AVR of different manufacturers working together.

This dataset will be assigned to a GOOSE control block (goCB) where some GOOSE service operation parameters will be configured, e.g. appID, confRev,goID,etc.

And it will be in the Communication section within CID file where some other essential parameters for GOOSE service will be configured, e.g. VLAN-ID, VLAN-PRIORITY or MAC ADDRESS.

Every AVR will publish its data this way, and every AVR will have to subscribe to the GOOSE messages published by the other AVR in the system. With this subscription, AVR will be able to obtain data to perform the master-follower method and the circulating current method, as well as any other logic/automatism that could be necessary.

Topological information of the busbars and the transformers is absolutely necessary to put in service any of these methods. With this information, AVR can determine which other AVR are working in parallel, and therefore AVR can decide within its internal logic which information received by GOOSE is used and which not. This topological information, basically circuit breakers' and isolators' statuses, can be obtained by subscription to GOOSE messages from other IED, like bay control units (BCU). These BCU will provide information about XCBR and XSWI logical nodes.

GOOSE service has a mechanism that tries to guaranty the reception of data by repetition of the messages. But even most important in this case, GOOSE service provides another mechanism to detect the communication failure of any one of AVR. This kind of failure could provoke a bad operation of the other AVR. Therefore, once it's detected, all AVR belonging to the same parallel group will be blocked.

The application of GOOSE service enables and makes easier the implementation of other substation automatism or user logics, e.g. automatisms that, after a protection event, connect to the substation a power transformer working in hot-standby.

Additionally, the latest version of IEC 61850 standards provide a seamless redundancy protocol that is IEC 62439-3 Ed.2.0: Industrial communication networks – High availability automation networks - Part 3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR). With any of these two protocols (PRP and HSR), reliability of parallel transformers control methods increases significantly.

V. RTDS TEST CASES

In order to probe the algorithm used in the circulating current method, 45MVA, 138±13x5%/36 kV, YNd11 power transformers are simulated in a RTDS and placed under different situations.

i. Two transformers in parallel with the same source

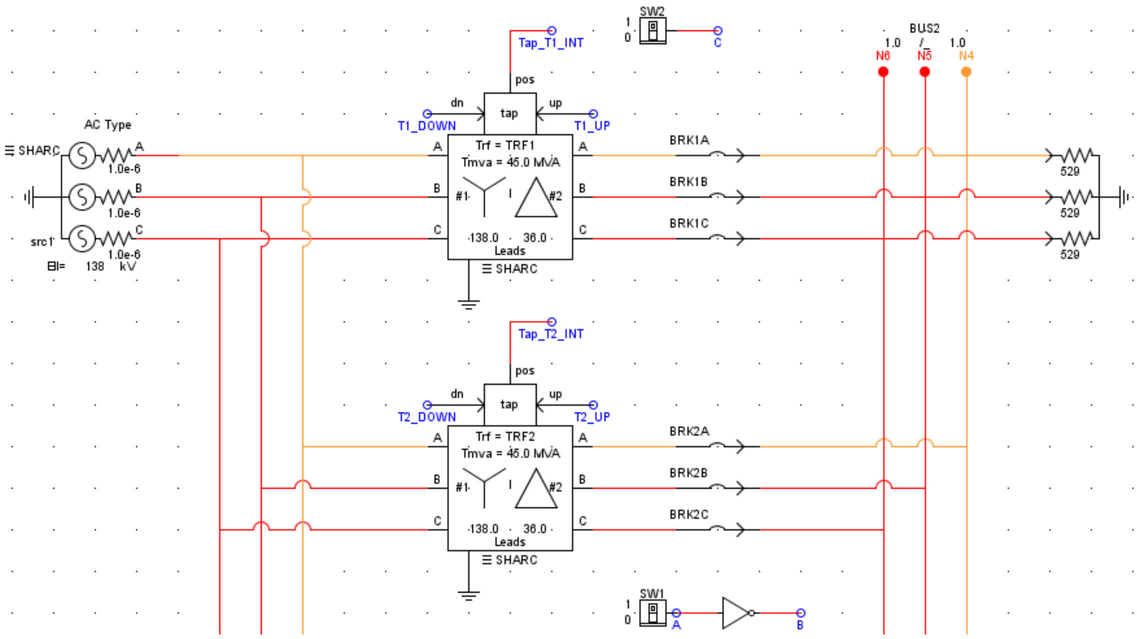

Figure 1. RTDS simulation of two power transformers in parallel feeded with the same source.

Taking into account that the transformers used in the simulation are the ones described before, the circulating current for one step of difference between them can be calculated in the following way:

$$V_{per\ tap} = 0.05\% \times \frac{36kV}{\sqrt{3}} = 1039V$$

$$Z_{LOOP} = 2 \times Z_{TRF} = 2 \times [12\% \times Z_{BASE}] = 2 \times \left[12\% \times \frac{V_{BASE}}{I_{BASE}}\right]$$

$$= 2 \times \left[12\% \times \frac{36kV}{1250A}\right] = 6{,}912\Omega$$

As it is going to be pure reactive, $Z_{LOOP} = j6{,}912\ \Omega$

$$\text{So,} \quad I_{CIRC} = \frac{1039V}{j6{,}912\ \Omega} = -j150{,}318A$$

Another way of calculating the circulating current could be reducing the system into the equivalent circuit and placing a source that will represent the difference in taps between both transformers. In this example it is shown just one step of difference because this calculation will be used along the different test cases.

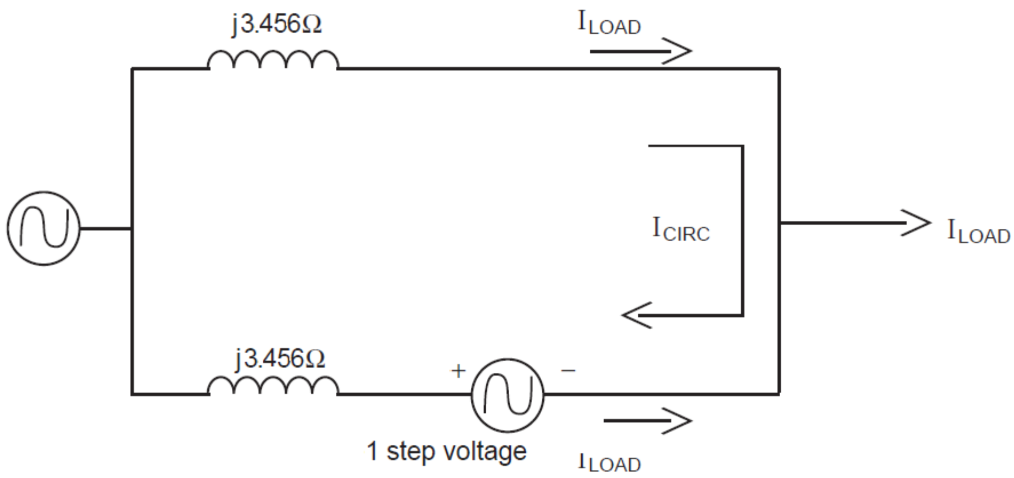

Figure 2. Equivalent circuit with one step tap discrepancy

$$I_1 \times Z_1 = I_2 \times Z_2 - \Delta V$$

$$I_1 \times Z_1 - I_2 \times Z_2 = -\Delta V$$

$$(I_1 - I_2)Z_1 = -\Delta V$$

$$(I_1 - I_2) = -\frac{\Delta V}{Z_1} = -300{,}6365$$

$$(I_L + I_{CIRC}) - (I_L - I_{CIRC}) = -\frac{\Delta V}{Z_1} => I_{CIRC} = -j150{,}31A$$

Two cases are going to be taken into account. In the first one the effect of three different tap steps is going to be shown while in the second one, in normal operation with both transformers being in the same tap position, the source is going to be modified.

In any case, the AVRs will calculate a compensated voltage setpoint (VCOMP) that depends on the amount of circulating current present in the system and will use it instead of the initial setting of the voltage setpoint (VCON):

$$V_{COMP}(\%) = V_{CON}(\%) + K_R(\%) \times \frac{I_{CIRC}}{0{,}1 \times I_N} \quad [1]$$

$$K_R(\%) = \frac{X_1(\%) + X_2(\%)}{10} \quad [1]$$

The AVRs will operate when the deviation between the voltage measured in the bus and the compensated voltage setpoint is greater than the insensitivity degree (GI) which will define the area where we want to have the bus voltage. During the tests, the GI is going to be set in a value of 3%, so:

$$DV(\%) = V_{COMP}(\%) - V_{BUS}(\%) \quad [1]$$

$$if\ |DV(\%)| > 3\% \Rightarrow OPERATION\ of\ the\ AVR\ \ [1]$$

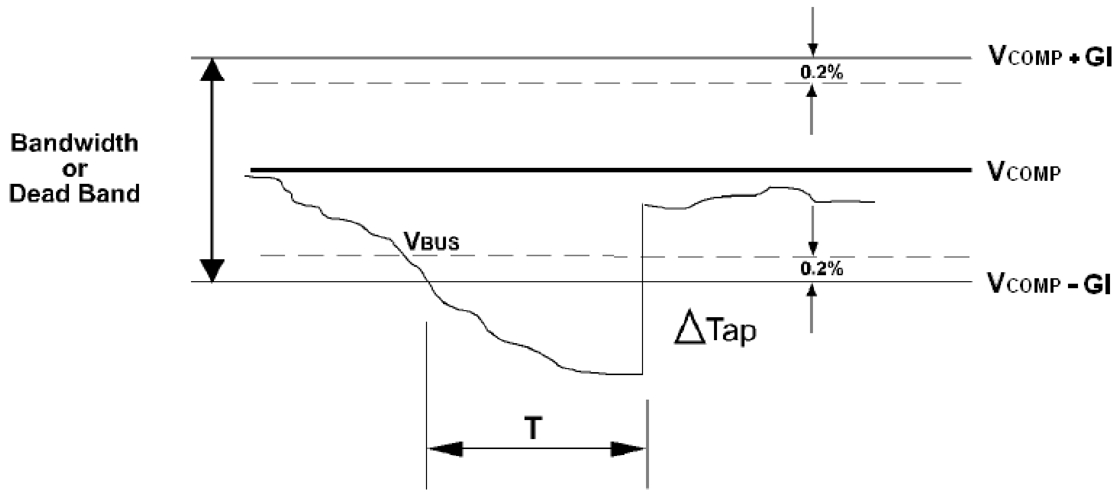

Figure 3.Dead band and AVR operation

In the first test case, the transformers are going to be placed in different tap positions, transformer one in tap number 17 and transformer two in tap 14, which is the central tap of the tapchanger. This could be a common situation in those systems with no supervision control where placing transformers with different tap positions is allowed. The second transformer is feeding the load and the first one is placed in parallel (there are 138kV in the HV side).

A circulating current appears due to the 3 taps difference.

$$I_{CIRC} = 3 \times -j150{,}31A = -j451A$$

And the AVRs calculate a compensated setpoint voltage:

$$V_{COMP}(\%)_{T1} = 100(\%) + 2{,}4(\%) \times \frac{-451}{0{,}1 \times 1250} = 91{,}34$$

$$V_{COMP}(\%)_{T2} = 100(\%) + 2{,}4(\%) \times \frac{451}{0{,}1 \times 1250} = 108{,}695$$

Depending on the amount of deviation between the measured voltage and the compensated voltage setpoint, the AVRs will operate faster or slower and once one operates the amount of circulating current changes. The time the AVR waits up to the moment it starts giving commands is a curve depending time with a minimum time of operation (in this case an inverse curve with dial 2 and minimum time of operation of 10 seconds), the following commands, if the measured voltage is still out of the dead band, will be given always with the same definite time (in this case 5 seconds).

In this situation transformer one starts tapping down up to the moment it reaches the tap of the second transformer.

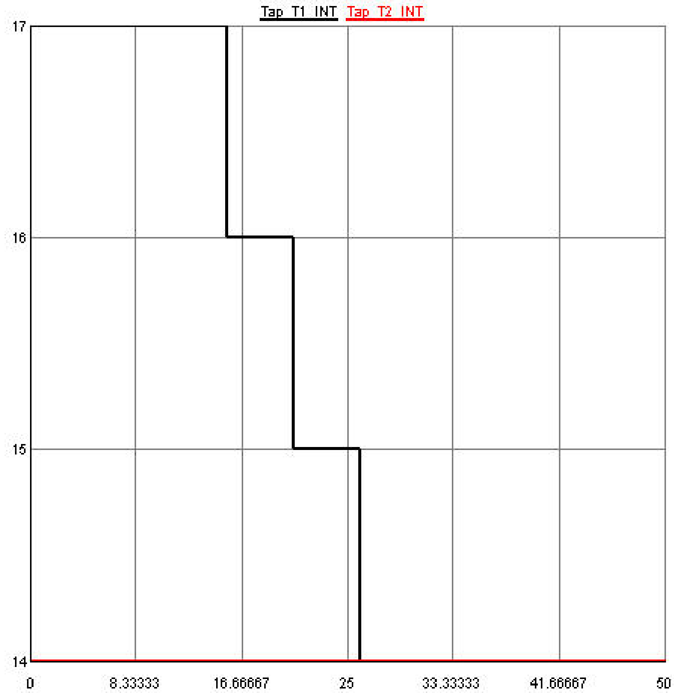

Figure 4. Tap status of two transformers with the same source and different initial taps

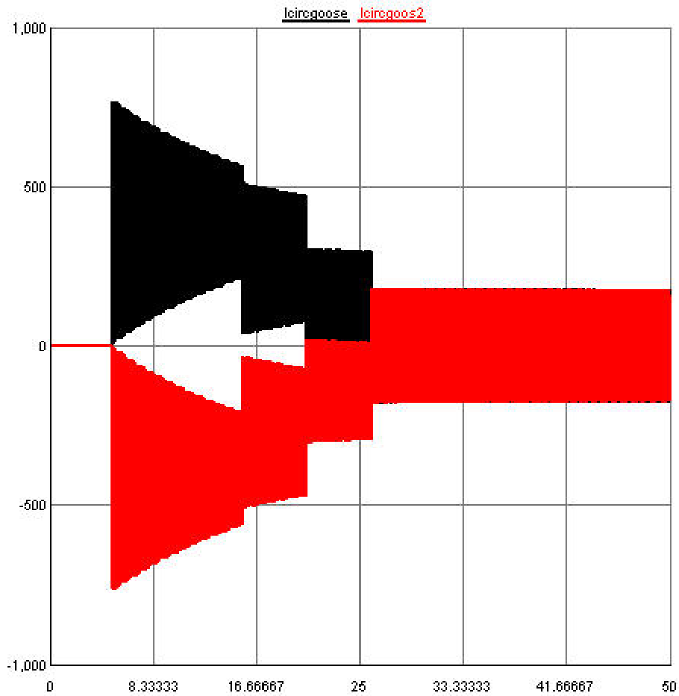

Figure 5. Circulating current of two transformers with the same source and different initial taps

When both transformers are working in parallel situation and the source decreases a 10%, from 138kV to 124kV, both AVRs at the same time give two tap up commands to keep the voltage in the bus constant.

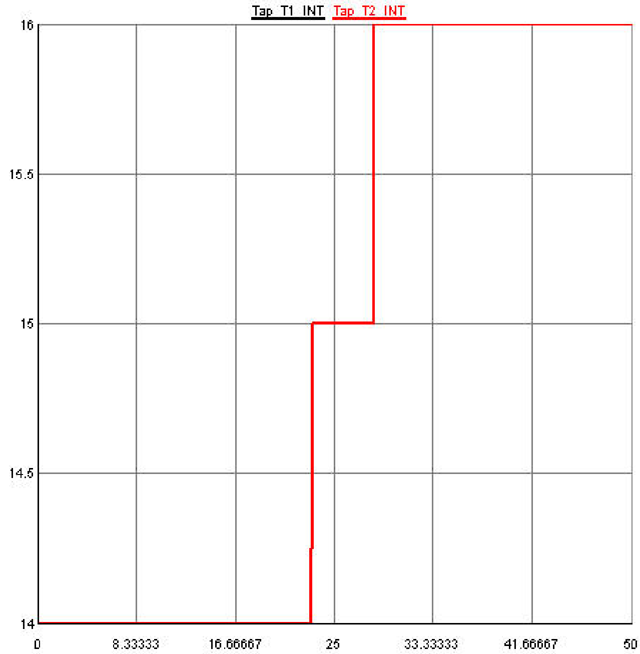

Figure 6. Tap status of two transformers after decreasing the source

ii. Three transformers in parallel with the same source

Nowadays more and more utilities are using, in certain occasions, three transformers in parallel. The real RTDS circuit and the equivalent circuits that are going to be studied, where the first transformer is in tap number 17, the second transformer is in tap number 14 and the third one is in tap number 10, can be found below.

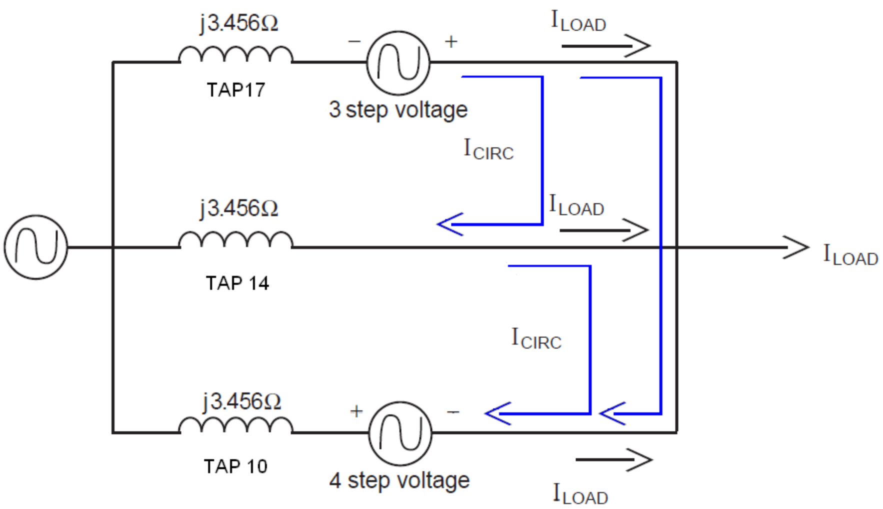

Figure 7. Equivalent circuit of three transformers with tap discrepancy

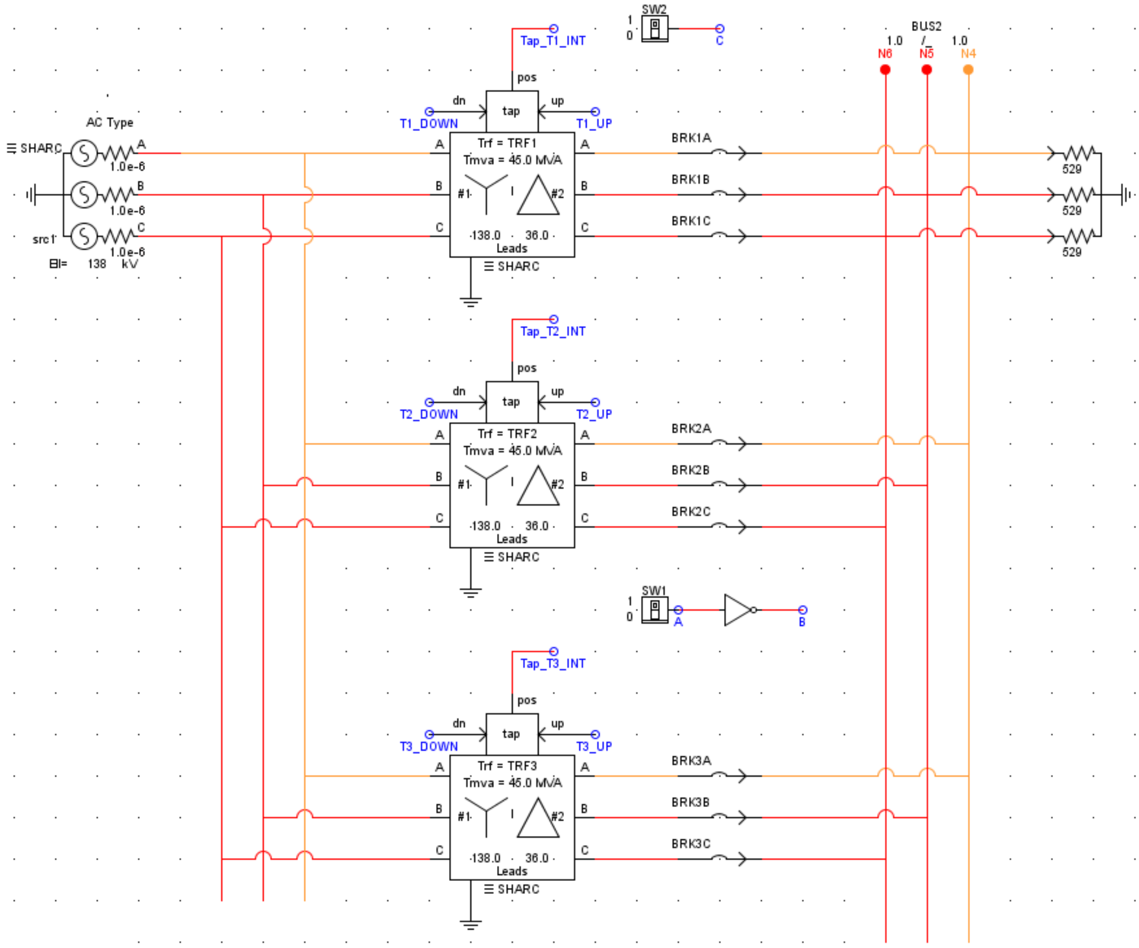

Figure 8. RTDS simulation of three power transformers in parallel feeded with the same source.

The circulating current flowing between the transformers will appear due to the tap discrepancy:

$$I_{CIRC12} = -j451A \text{ (Difference of 3 taps)}$$

$$I_{CIRC23} = -j601A \text{ (Difference of 4 taps)}$$

$$I_{CIRC13} = -j1052{,}226A \text{ (Difference of 7 taps)}$$

And the final resulting current the AVRs will try to reduce is:

$$I_{L1} = I_L + I_{CIRC12} + I_{CIRC13} = I_L - j1503{,}226$$

$$I_{L2} = I_L - I_{CIRC12} + I_{CIRC23} = I_L - j150$$

$$I_{L3} = I_L - I_{CIRC13} - I_{CIRC23} = I_L + j1653{,}226$$

The compensated voltage setpoint, as it has already been explained, will depend on these circulating currents. The AVRs will allow modifying the voltage setpoint in a maximum value of 15% (modified by setting), so that we can ensure that they will try to reduce the circulating current without compromising the initial setpoint of the bus voltage. We must remember that the main purpose of the AVR is maintaining the bus voltage at a given set point (or in the load if the line drop compensation method is also used) while trying also to reduce the circulating current if possible.

$$V_{COMP}(\%)_{T1} = 100(\%) + 2,4(\%) \times \frac{-1503,226}{0,1 \times 1250} = 71,13\% \text{ −> } 85\%$$

$$V_{COMP}(\%)_{T2} = 100(\%) + 2,4(\%) \times \frac{-150}{0,1 \times 1250} = 97,12\%$$

$$V_{COMP}(\%)_{T3} = 100(\%) + 2,4(\%) \times \frac{1653,226}{0,1 \times 1250} = 131,74\% \rightarrow 115\%$$

$$|DV_{T1}(\%)| > 3\% \Rightarrow \text{OPERATION}$$

$$|DV_{T2}(\%)| < 3\% \Rightarrow \text{NO OPERATION}$$

$$|DV_{T3}(\%)| > 3\% \Rightarrow \text{OPERATION} \rightarrow \text{FASTER}$$

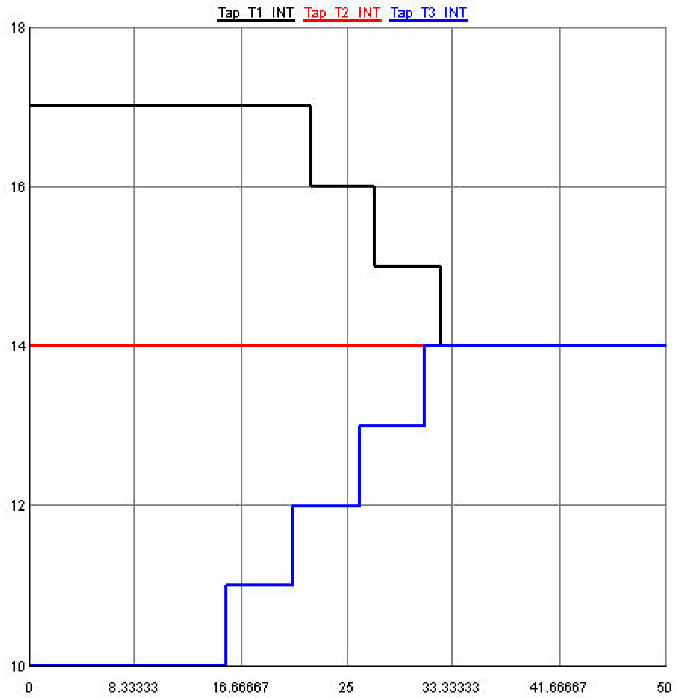

Figure 9. Tap status of three transformers with the same source and different initial taps

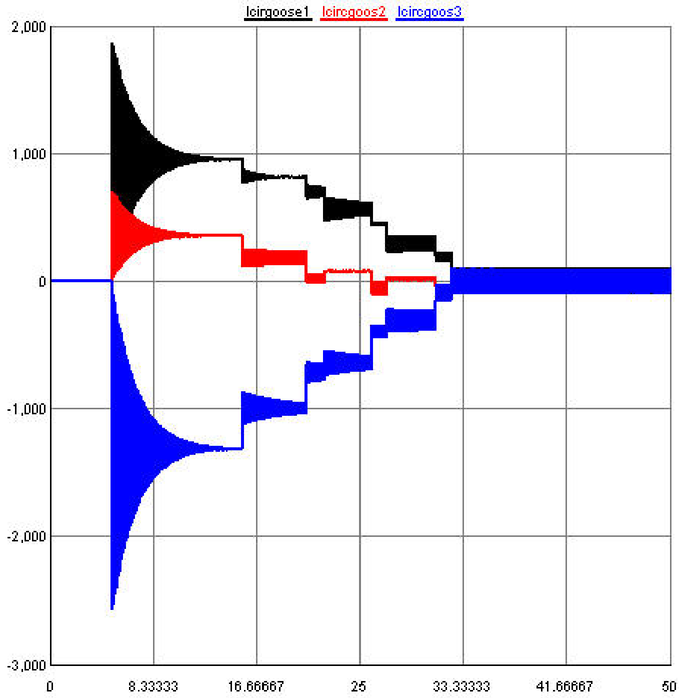

Figure 10. Circulating current of three transformers with the same source and different initial taps

When the three transformers are working in the same tap position (tap number 14), and the source decreases a 10%, from 138kV to 124kV, the three AVRs operate at the same time tapping up twice to keep the bus voltage inside the dead band.

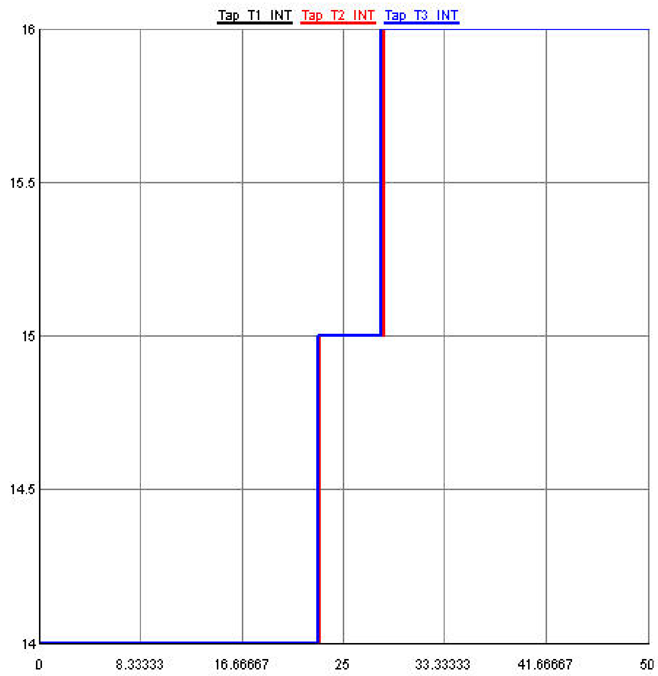

Figure 11. Tap status of three transformers after decreasing the source

iii. Five transformers in parallel

The circulating current method proposed, allows working with up to five parallel transformers. Like in the cases shown before, working with two or three parallel transformers, when all the transformers are located in the same tap position and the source in the HV is modified, all the AVRs operate at the same time tapping up or down and therefore keeping the bus voltage inside the dead band, but, what happens when five transformers start working in parallel conditions coming from different tap positions having 138kV in the HV side?

In this case the transformers are going to be placed in parallel as shown below.

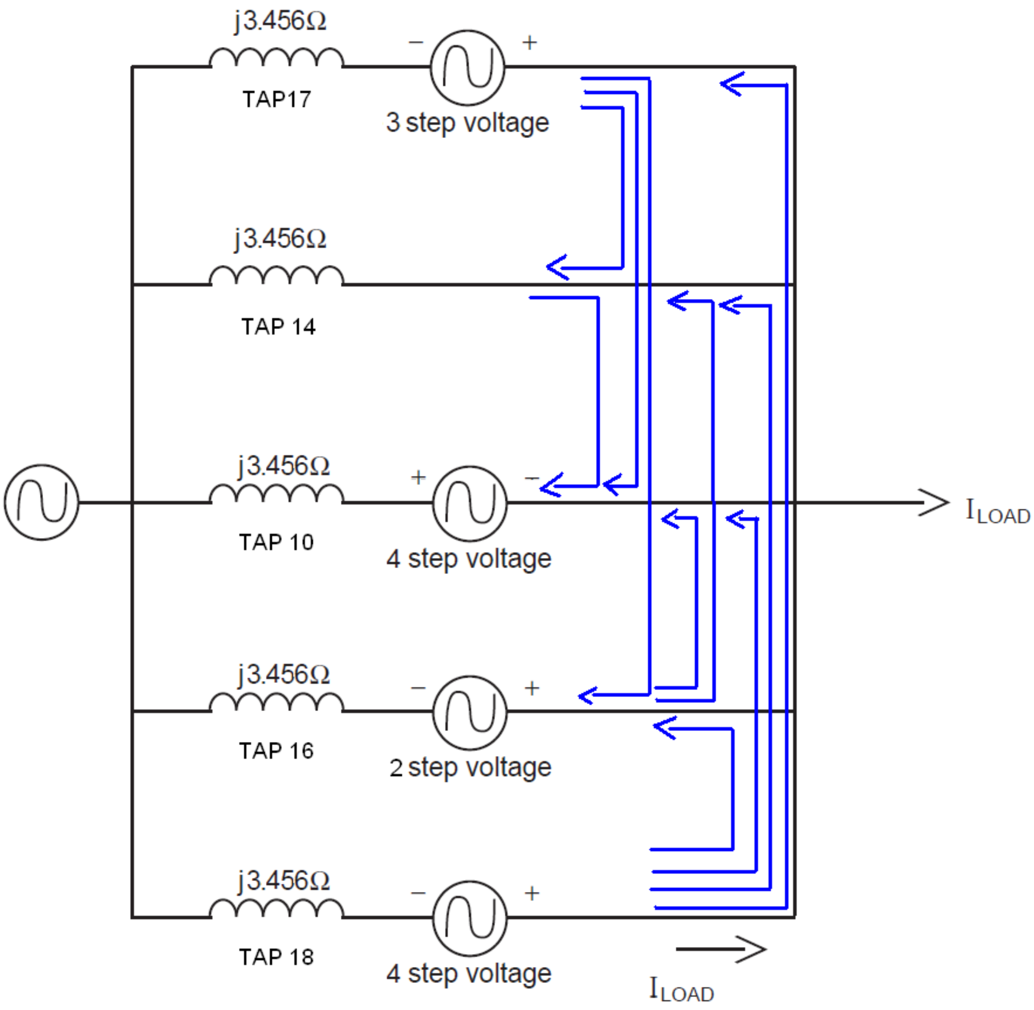

Figure 12. Equivalent circuit of five transformers with tap discrepancy

The circulating currents flowing from one transformer to another would be:

$$I_{CIRC12} = -j451A \text{ (Difference of 3 taps)}$$

$$I_{CIRC13} = -j1052{,}226A \text{ (Difference of 7 taps)}$$

$$I_{CIRC14} = -j150{,}31A \text{ (Difference of 1 tap)}$$

$$I_{CIRC23} = -j601A \text{ (Difference of 4 taps)}$$

$$I_{CIRC42} = -j300{,}62A \text{ (Difference of 2 taps)}$$

$$I_{CIRC43} = -j901{,}86A \text{ (Difference of 6 taps)}$$

$$I_{CIRC51} = -j150{,}31A \text{ (Difference of 1 tap)}$$

$$I_{CIRC52} = -j601A \text{ (Difference of 4 taps)}$$

$$I_{CIRC53} = -j1202{,}48A \text{ (Difference of 8 taps)}$$

$$I_{CIRC54} = -j300{,}62A \text{ (Difference of 2 taps)}$$

And therefore, the currents to be reduced by the AVRs are:

$$I_{L1} = I_L + I_{CIRC12} + I_{CIRC13} + I_{CIRC14} - I_{CIRC51} = I_L - j1352{,}916$$

$$I_{L2} = I_L + I_{CIRC23} - I_{CIRC12} - I_{CIRC42} - I_{CIRC52} = I_L + j751{,}62$$

$$I_{L3} = I_L - I_{CIRC13} - I_{CIRC23} - I_{CIRC43} - I_{CIRC53} = I_L + j3757{,}386$$

$$I_{L4} = I_L + I_{CIRC42} + I_{CIRC43} - I_{CIRC14} - I_{CIRC54} = I_L - j751{,}55$$

$$I_{L5} = I_L + I_{CIRC51} + I_{CIRC52} + I_{CIRC53} + I_{CIRC54} = I_L - j2254{,}41$$

Having a look over the compensated setpoint voltage values it can be seen how the third transformer will operate earlier than the others:

$$V_{COMP}(\%)_{T1} = 100(\%) + 2{,}4(\%) \times \frac{-1352{,}916}{0{,}1 \times 1250} = 74{,}024\% \rightarrow 85\%$$

$$V_{COMP}(\%)_{T2} = 100(\%) + 2{,}4(\%) \times \frac{751{,}62}{0{,}1 \times 1250} = 114{,}43\%$$

$$V_{COMP}(\%)_{T3} = 100(\%) + 2{,}4(\%) \times \frac{3757{,}386}{0{,}1 \times 1250} = 172{,}14 \rightarrow 115\%$$

$$V_{COMP}(\%)_{T4} = 100(\%) + 2{,}4(\%) \times \frac{-751{,}55}{0{,}1 \times 1250} = 85{,}57$$

$$V_{COMP}(\%)_{T5} = 100(\%) + 2{,}4(\%) \times \frac{-2254{,}41}{0{,}1 \times 1250} = 56{,}71 \rightarrow 85\%$$

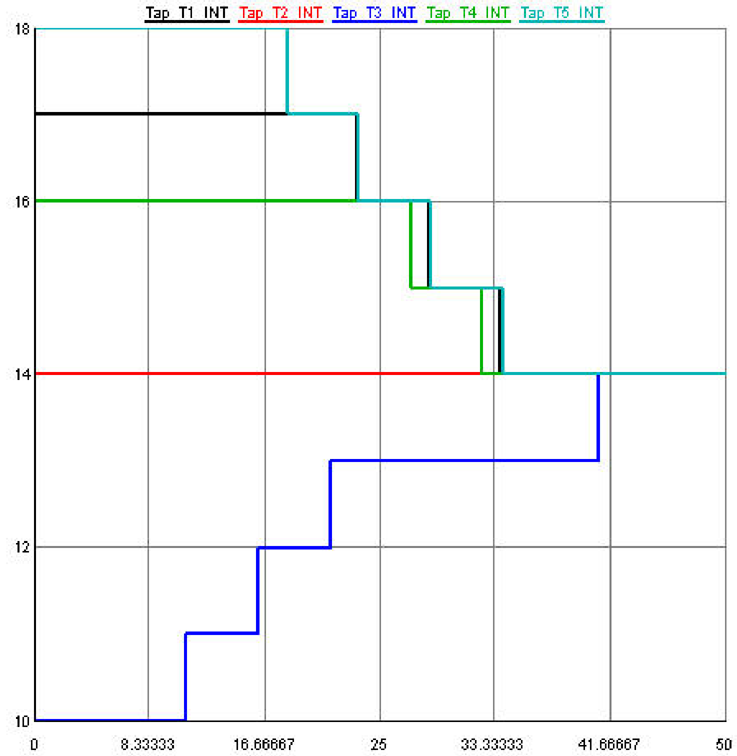

Figure 13. Tap status of five transformers with the same source and different initial taps

Finally, after many tap commands, the five transformers reach the medium tap position, tap number 14, and the circulating currents are reduced.

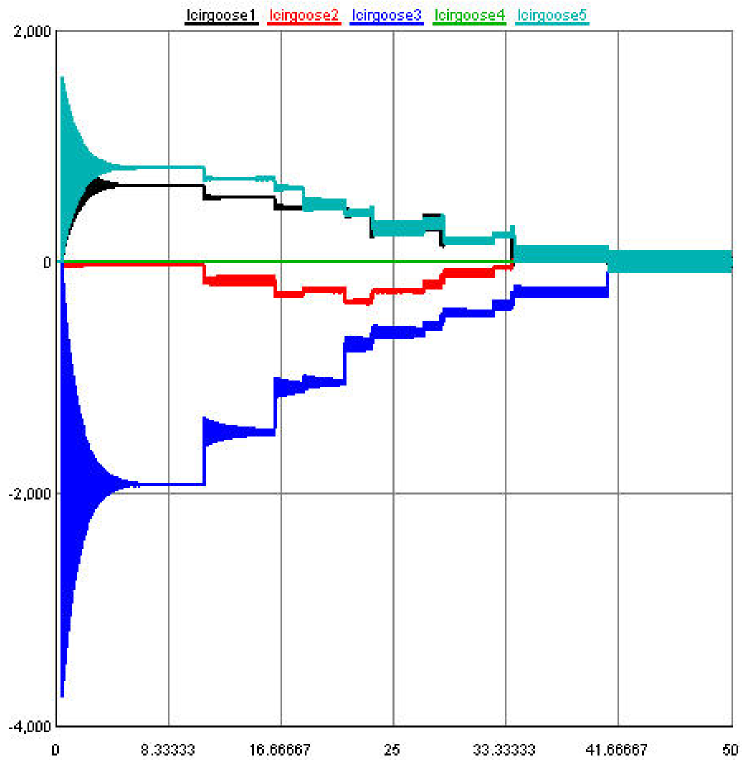

Figure 14. Circulating current of five transformers with the same source and different initial taps

iv. Source side separation application

There are many applications in which the transformers are going to operate in parallel conditions but the input HV lines are different. In this simulation, the first transformer is going to be connected to a source with almost cero impedance ($1.0e^{-6}\Omega$) while the second one is going to be feeded by a source with an impedance value of 10Ω.

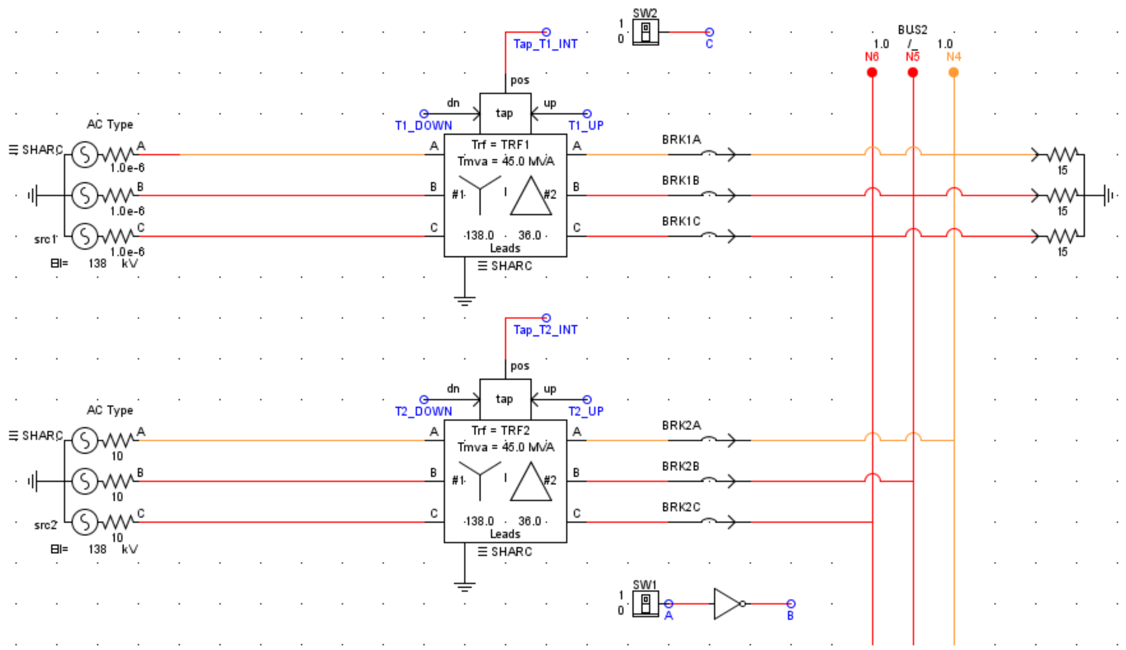

Figure 15. RTDS simulation of two power transformers in parallel feeded with different sources.

Due to the difference in impedances between each source and the bus, the pure load currents in both transformers will be different (refer to figure 4.c), creating a circulating current, although both transformers are working in the same tap position (tap number 14). As the method described in this paper only considers the reactive component of the circulating current it will achieve by tap changes a reduction of this component (tap changes will not allow the reduction of the active component of the circulating current).

The second AVR gives a tap up command while the first one stays in the initial one, tap number 14, with no operation.

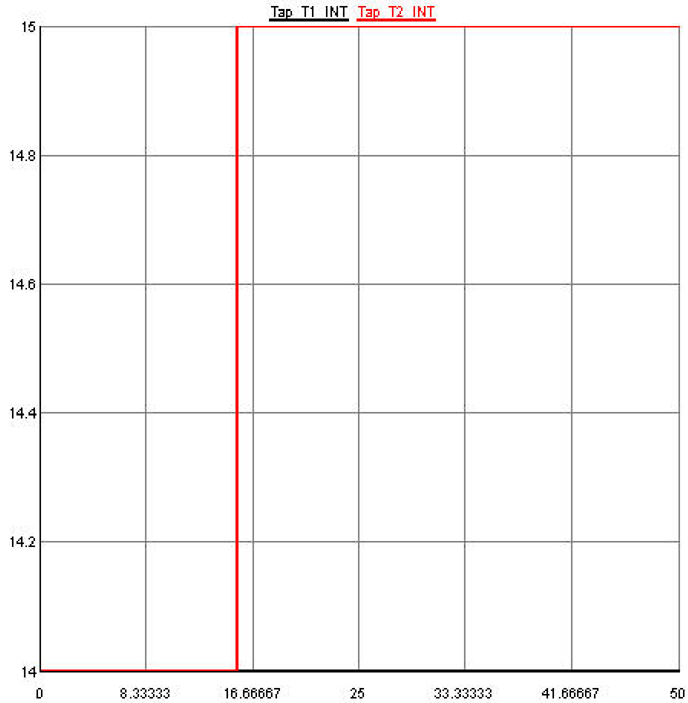

Figure 16. Tap status of two transformers with different sources and same initial taps

It can be shown how when both transformers are in the same tap, there is a circulating current which is decreased after the operation of the second AVR. The circulating current is not totally reduced due to the fact that the AVRs are trying also to maintain the bus voltage constant.

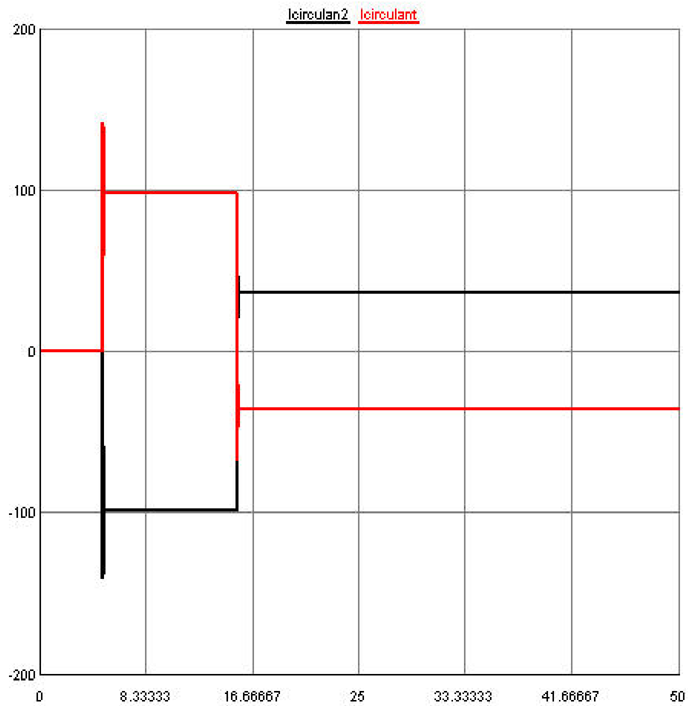

Figure 17. Circulating current of two transformers with different sources and same initial taps

The same thing happens when the transformers start working in different taps. Apart from the fact that the circulating current appears because of the different sources, the tap discrepancy will also increase it so both effects are going to be added. The AVRs start giving tap commands and reducing the circulating as much as possible keeping the bus voltage constant.

v. Paralleling transformers with different characteristics

While the set-up of new substations involves an engineering process where all the elements are selected accordingly, for instance the characteristics of the transformers that are going to work in parallel conditions are similar, in those old substations that are being renewed slowly or in those cases in which one transformer is damaged and must be replaced with another one, the characteristics of the new transformer normally do not fit with the existing one.

In this test the impedances of the transformers are going to be modified as much as possible to be able to see the effect. The K_R factor used to calculate the compensated setpoint voltage can take a maximum value of 5% so, the impedances used for the simulations are going to be a 12% for the first transformer and a 38% for the second one.

To be able to see the real effect of the impedance difference, the transformers are going to start in the same tap position, tap number 14. In this situation the reactive power is going to be really different between them and after the operation of the AVRs, the final reactive power of both transformers is going to be almost similar while the active power does not change.

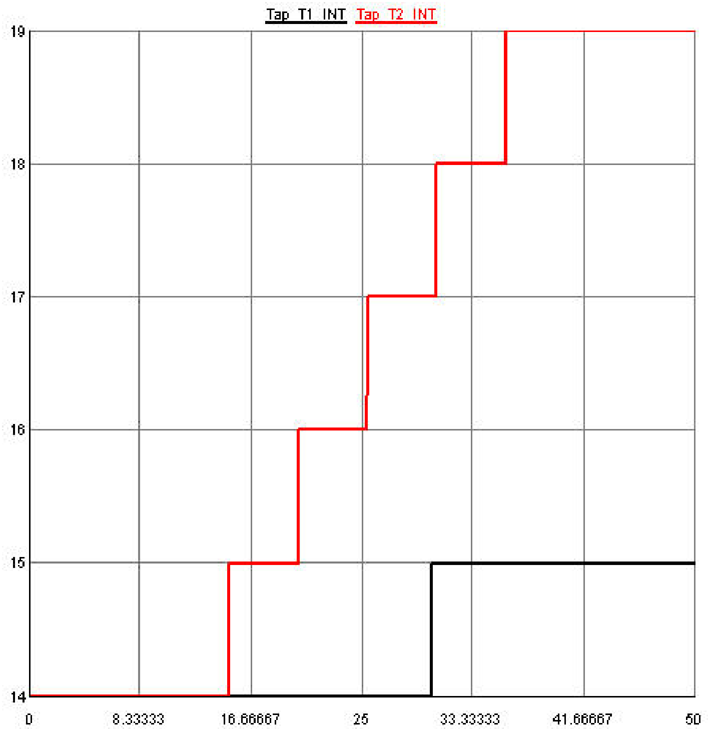

Figure 18. Tap status of two transformers with different characteristics and same initial taps

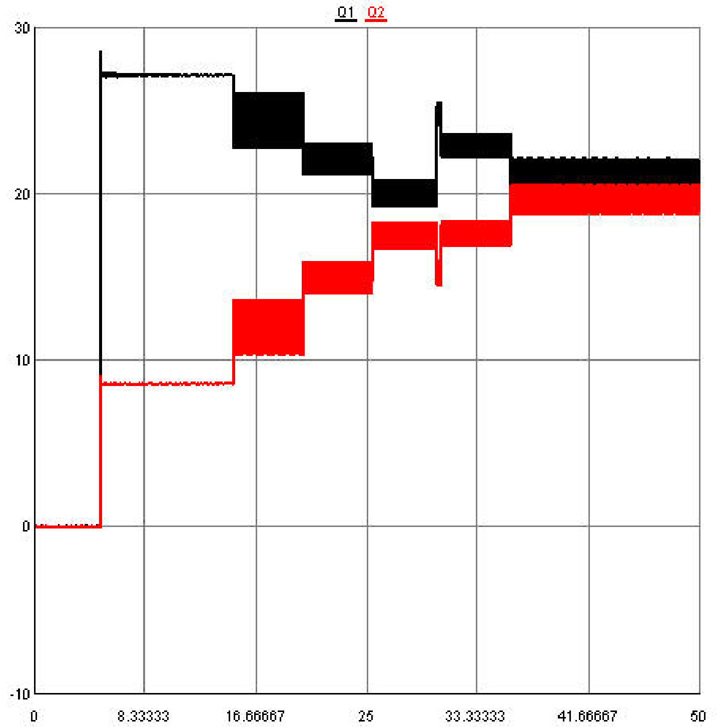

Figure 19. Reactive power of two transformers with different characteristics and same initial taps

The same thing happens when the transformers are at the first moment in different taps. In this case the tap discrepancy effect is added to the effect of the different characteristics.

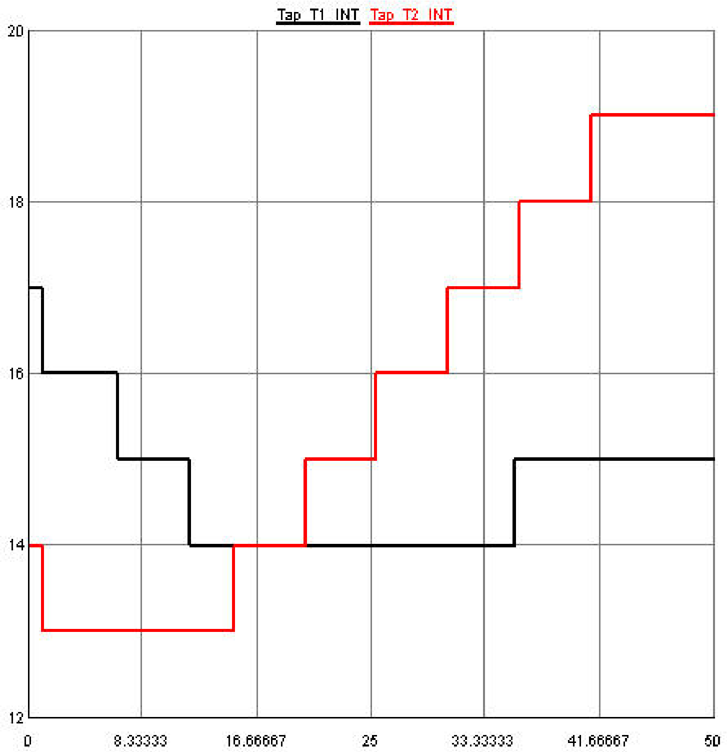

Figure 20. Tap status of two transformers with different characteristics and tap discrepancy

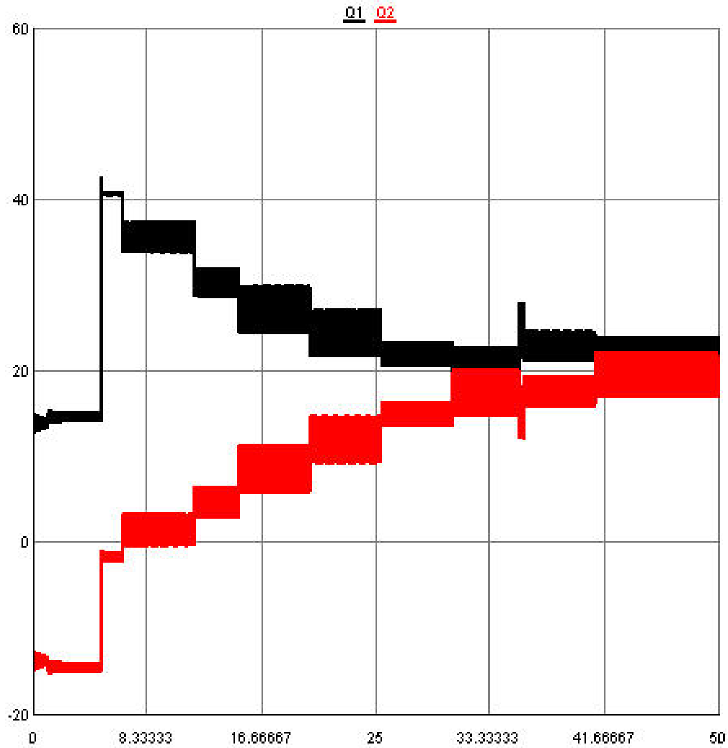

Figure 21. Reactive power of two transformers with different characteristics and tap discrepancy

vi. Problems with the tapchanger

The circulating current method does not consider the possibility of any kind of damage in the wiring of the output contacts of the IEDs or even in the tapchanger itself. If something like that happens being both transformers in the same tap, when there is a change in the HV side and the bus voltage goes out of the dead band, both AVRs will operate but just one transformer will change the necessary taps, modifying the bus voltage and ensuring the voltage supply. In this new situation, a circulating current appears due to the tap discrepancy. The AVR which is connected to the damaged tapchanger will keep on giving tap commands up to the moment it goes to a block status because the measured voltage has been out of the regulation range for a long time (time defined by the user). The AVR which is connected to the tapchanger that operates correctly is inside the dead band so it does not operate.

vii. Paralleling interruption and backup transformer

Many utilities are used to work with two transformers in parallel conditions, having a third transformer as backup. This third transformer can be used during maintenance works or when there is any protection trip in one of the transformers that are in service.

When there is any kind of maintenance work arranged, before closing the breaker of the backup bay, the operators firstly place the backup transformer in the same tap position the transformers in service are.

In those substations with a backup transformer, when there is a protection trip in one of the transformer bays in service, a control system gives a close command over the backup bay to ensure that two transformers are always operating in parallel conditions. Normally a tap discrepancy is going to be between the transformers and therefore a circulating current is going to appear. The circulating current method will reduce it by bringing the backup transformer into the tap the service transformer is.

In the simulation transformers one and two are operating in tap number 14, while the backup transformer is in tap number 8. A trip is generated in the second bay and the third transformer comes automatically into the system.

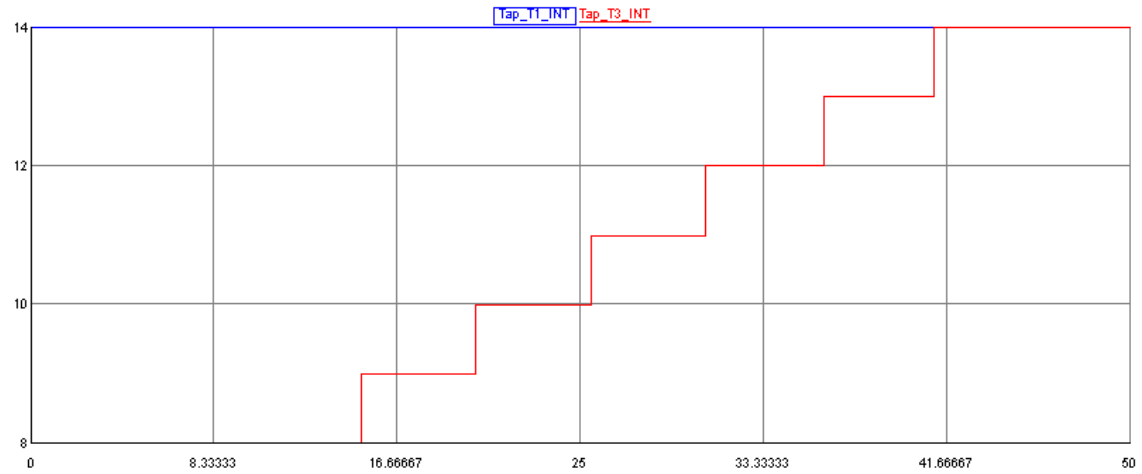

Figure 22. Tap status when a backup transformer comes into the system

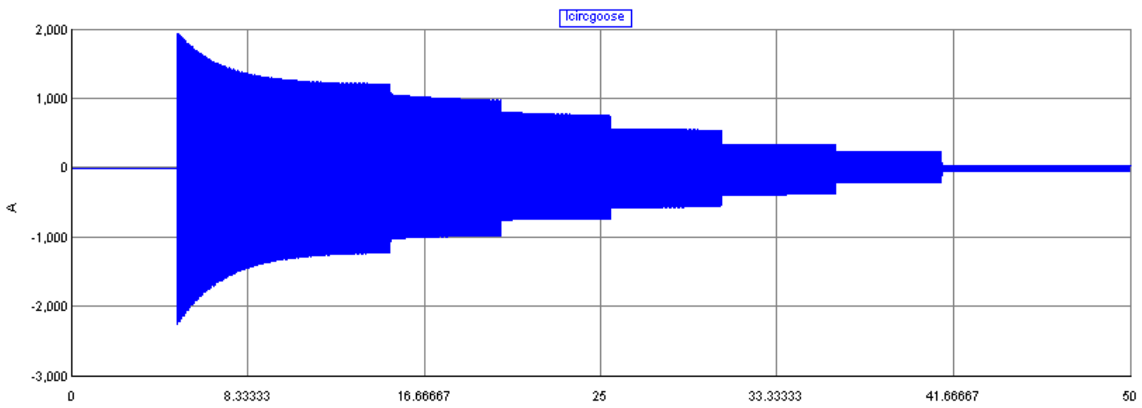

Figure 23. Circulating current when a backup transformer comes into the system

VI. CONCLUSION

Several control methods for paralleled transformers have been used along the years. All of them have advantages and disadvantages. This paper has taken into account the three main ones, covering in depth the circulating current method and highlighting the advantages of implementing those control methods by means of IEC 61850 technologies.

IEC 61850 standards are very wide-ranging, but this paper propose only to make use of the GOOSE communication service. It is a multicast service that allows IEC 61850 servers to communicate information between them, and therefore it allows to design a decentralized automatisms without any kind of wiring.

The solution based on this technology provides a lot of advantages, between them, cost reduction (minimizing the wiring), open solution (no proprietary communication interface), flexibility (for different utilities and requirements and possibility for future expansions) and reliability.

Reliability of power system is increasingly important. We could say that reliability is a must. From that point of view, IEC 61850 and particularly GOOSE messages provide a very high level of reliability. GOOSE service includes a repetition mechanism and a communication failure detection mechanism that assure that published data will be received sooner or later, and that the required countermeasures will be adopted as soon as a communication failure is detected to avoid bad operations. And the latest version of IEC 61850 standards provides two options for seamless redundancy protocols, PRP and HSR, both of them described in IEC 62439-3 standard.

Furthermore, the application of GOOSE service enables and makes easier the implementation of other substation automatism or user logics, for instance, automatisms that, after a protection event, connect to the substation a power transformer working in hot-standby. What is more, there are situations that require the exchange of blocking signals for a correct operation of the system, such situations could be for example when there is any damaged tapchanger or when there is a capacitor bank working in automatic mode together with the AVRs. In this last case in particular, when the capacitor bank and the AVR are working in automatic mode, the voltage variations produced by them (when the capacitor bank is closed or the AVR taps up and down) could make both regulation methods come into conflict.

Reactive power is the key to an efficient and reliable grid and even if the impedance difference between the parallel transformers is extreme, the circulating current method operates accordingly balancing the reactive power.

While many different situations have been tested in a RTDS using the circulating current method, where just the reactive power is share between the AVRs, a good performance of the master slave method needs a complex feedback system to guarantee that the operations executed by each follower AVR are correct. This method also assumes that the relative tap positions between transformers remain constant for all system conditions.

In any case, what must be clear is that the AVR main purpose is maintaining the bus voltage at a given setpoint keeping also constant the load voltage, and this cannot be compromised because of the fact of reducing the circulating current that appears between the parallel transformers.

It would be also interesting to analyze the paralleling operation taking into account the effects of the line drop compensation settings and the action of the reverse power detection.

I. REFERENCES

[1] Instruction Manual. ZIV Automatic Voltage Regulator IEC Model RTV, Zamudio (Spain), Reference BRTV1110Dv03 2013.