Analysis and design of a three-phase constant voltage transformer based on ferroresonance

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Applications requiring a constant terminal voltage may benefit from using a distribution transformer based on ferroresonance. This transformer guarantees an output voltage complying with all standards for large fluctuations in input voltage (going up to ±30%). This offers significant advantages over on-load tap changer control for certain applications, and can be an alternative for power electronic based systems.

The three-phase constant-voltage-transformer (CVT) consists of three capacitors and six saturable inductors. The windings on the three cores marked with S, are connected in series with the zigzag connected windings on the cores marked with Z. The operating principle is based on the saturation of 5 cores out of 6 at any given instant in time. The other winding carries a nearly constant voltage, determined by the frequency, the number of windings and the magnetic characteristic of the core. The linear inductors L ensure a decoupling of grid and transformer voltage. The capacitors supply the necessary reactive energy to drive the cores into saturation.

The first step in modelling consists in the derivation of a set of general design equations. A computer model for the simulation of the electric and magnetic variables is then set up and implemented in SPICE. This may serve to analyse the operation of the CVT in various operating conditions. Besides, the computer model proves to be an invaluable tool to optimise the design of the CVT.

A low power prototype has been built to validate the design equations. Measurements are compared with simulation results to test the accuracy of the numerical model. An excellent agreement is found between experiments and calculated results if component losses are taken into account properly.

The functionality of the prototype is evaluated with respect to efficiency, harmonic distortion, power factor and unbalanced operation. Losses are mainly caused by iron losses in the cores and by dielectric losses in the capacitors. The influence of different loading conditions has also been investigated. This includes the load power and the load angle. The prototype is found to work properly up to a maximum power demand, both for resistive as for partly capacitive or inductive loads.

A galvanic isolation may be needed and therefore, the functions of maintaining a constant voltage on the one hand, and transforming the voltage to a higher or lower level on the other hand, may be split up between a CVT and a distribution transformer. The effect of this isolating transformer on the operation has been studied.

From a technical point of view, a full scale 400 kVA CVT with an efficiency well above 99% and a total harmonic voltage distortion limited to 2%, may be designed. A cost analysis is imperative to investigate the economical feasibility of this project.

Analyse et conception d'un transformateur triphasé à tension constante, basé sur la ferrorésonance

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Certaines applications électriques, nécessitant une tension quasiment constante à leurs bornes, peuvent tirer avantage d'un transformateur basé sur le principe de la ferrorésonance. Ce transformateur garantit une tension de sortie respectant toutes les normes pour de larges fluctuations en tension d'entrée (allant jusqu'à ±30%). Ceci peut générer des avantages significatifs comparé à d'autres solutions et même devenir un alternatif dans certains cas, comme par exemple pour le régleur de prises sous charge ou pour des systèmes basés sur l'électronique de puissance.

Le transformateur triphasé à tension constante (CVT, d'après son acronyme anglais) est constitué de trois capacités et de six inductances saturables. Les enroulements autour des 3 noyaux désignés par S, sont connectés en série avec les enroulements en zigzag autour des 3 noyaux désignés par Z. Le principe d'opération est basé sur le fait qu'à chaque moment cinq des six noyaux sont saturés. L'autre enroulement porte une tension quasiment constante, qui est déterminée par la fréquence, le nombre de tours et la caractéristique magnétique du noyau. Des inductances linéaires L assurent le découplage entre le réseau et la sortie du transformateur. Les capacités délivrent la puissance réactive nécessaire pour forcer les noyaux à entrer dans la zone de saturation.

Le premier pas en modélisation consiste à développer un système d'équations descriptives. Un modèle numérique pour la simulation des quantités électriques et magnétiques peut ensuite être élaboré et introduit dans SPICE. Celui-ci peut servir à analyser le fonctionnement du CVT en différentes conditions d'opération. En plus, ce modèle est un outil indispensable pour optimiser le concept du CVT.

Un prototype à puissance réduite a été conçu pour valider les équations descriptives. Les mesures faites en laboratoire ont été comparées avec les résultats de simulation pour vérifier la précision du modèle numérique. Une correspondance excellente entre mesures et calculs a été trouvée, si les pertes des éléments ont été prises en compte convenablement.

Le fonctionnement du CVT à été évalué en ce qui concerne l'efficacité, la distorsion harmonique, le facteur de puissance et en mode déséquilibré. Les principales pertes sont les pertes fer dans les noyaux et les pertes diélectriques des capacités. L'influence de différentes conditions de charge a également été étudiée. Ce travail portait sur la puissance et l'angle de la charge. Le prototype a prouvé son bon fonctionnement jusqu'à une charge maximale admissible, et ceci pour des charges résistives et mixtes (avec composante inductive ou capacitive).

Si l'on a besoin d'une isolation galvanique, les fonctions qui permettent de maintenir une tension constante d'un côté, et la transformation vers un autre niveau de tension d'un autre côté, peuvent être partagées entre un CVT et un transformateur de distribution. L'influence de ce transformateur d'isolation a été étudiée.

Du point de vue technique, une efficacité supérieure à 99% peut être atteinte avec une distorsion harmonique des tensions inférieure à 2% pour un transformateur de 400 kVA. Finalement, une analyse économique est nécessaire pour évaluer la viabilité d'un tel projet.

ANALYSIS AND DESIGN OF A THREE-PHASE CONSTANT VOLTAGE TRANSFORMER BASED ON FERRORESONANCE

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SUMMARY

Applications requiring a constant terminal voltage may benefit from using a distribution transformer based on ferroresonance. This transformer guarantees an output voltage complying with all standards for large fluctuations in input voltage. This offers significant advantages over on-load tap changer control for certain applications, and can be an alternative for power electronic based systems.
In this paper the operation of a three-phase constant-voltage-transformer (CVT) is analysed, its behaviour is modelled, and this model is used in simulations.
A low power prototype has been built to validate the design equations. Measurements are compared to simulation results to test the accuracy of the numerical model. An excellent agreement is found between experiments and calculated results if component losses are taken into account properly.
The functionality of the prototype is evaluated with respect to efficiency, harmonic distortion, power factor and unbalanced operation. The influence of different loading conditions has also been investigated. The prototype is found to work properly up to a maximum power demand, both for resistive as for partly capacitive or inductive loads.

INTRODUCTION

The correct functioning of various electric and electronic appliances depends on the quality of the delivered electric power. Modern electronic loads are mostly fed through SMPS (Switch-Mode Power Supplies) that cause harmonic distortions in the distribution grid. Besides, the switching of large industrial loads can cause voltage dips up to 30 %, depending on the transient current and the short-circuit level of the grid. Special precautions can be necessary to guarantee the desired sinusoidal waveform with constant amplitude.
Another problem may occur in distribution substations, where a tertiary winding supplies the measuring and control equipment. Under varying load conditions a tap changer may be used to stabilise the secondary voltage by changing the number of primary windings. This implies that the tertiary voltage also should be controlled in order to have a constant voltage for the auxiliaries.

This paper focuses on the operation, modelling and prototyping of a possible solution for these power quality problems, the three-phase constant-voltage transformer. First, construction and operation of this device are explained. Then, the modelling of the different components is treated, leading to a device model that can be implemented in SPICE. Based on the derived design formulas, a prototype has been developed and tested. The influence of various phenomena is shown, both experimentally as well as by simulations. Finally, some conclusions are drawn on the practical use of the CVT.

OPERATION OF A THREE-PHASE CVT

The three-phase constant-voltage-transformer (CVT) is a static electromagnetic voltage stabiliser, supplying a sinusoidal voltage at its output, within a certain range of input voltage variations (1). The operation is based on the ferroresonance principle, a resonance phenomena involving a linear capacitor and a nonlinear inductor with matching impedances when the inductor core is saturated.
A simplified scheme is shown on figure 1. The circuit consists of three capacitors C and nine windings, wound on six different magnetic cores. The windings on the three cores marked by S, are connected in series with the zigzag connected windings on the cores marked by Z.
The operating principle is based on saturation of 5 out of 6 cores at any given instant in time. Consequently, the windings on these cores carry almost no voltage at that time. The other winding (windings) on the remaining core, carries (carry) a nearly constant voltage, determined by the frequency, the number of turns and the magnetic characteristic of the core.
The output voltage can thus be synthesised by different voltage blocks. Each of these blocks has a width corresponding to 1/12 of a period. The amplitude is determined by the number of turns on the non-saturated core. The desired sinusoidal output voltage can be obtained by choosing the number of turns N_S on a winding S equal to $\sqrt{3}$ times the number of turns N_Z on a winding *Z*. This is shown on figure 2.
The linear inductors L ensure a decoupling of grid and transformer output voltage. The capacitors supply the necessary reactive energy to drive the cores into saturation. On fig. 1 the load is Δ-connected, but this is not mandatory.

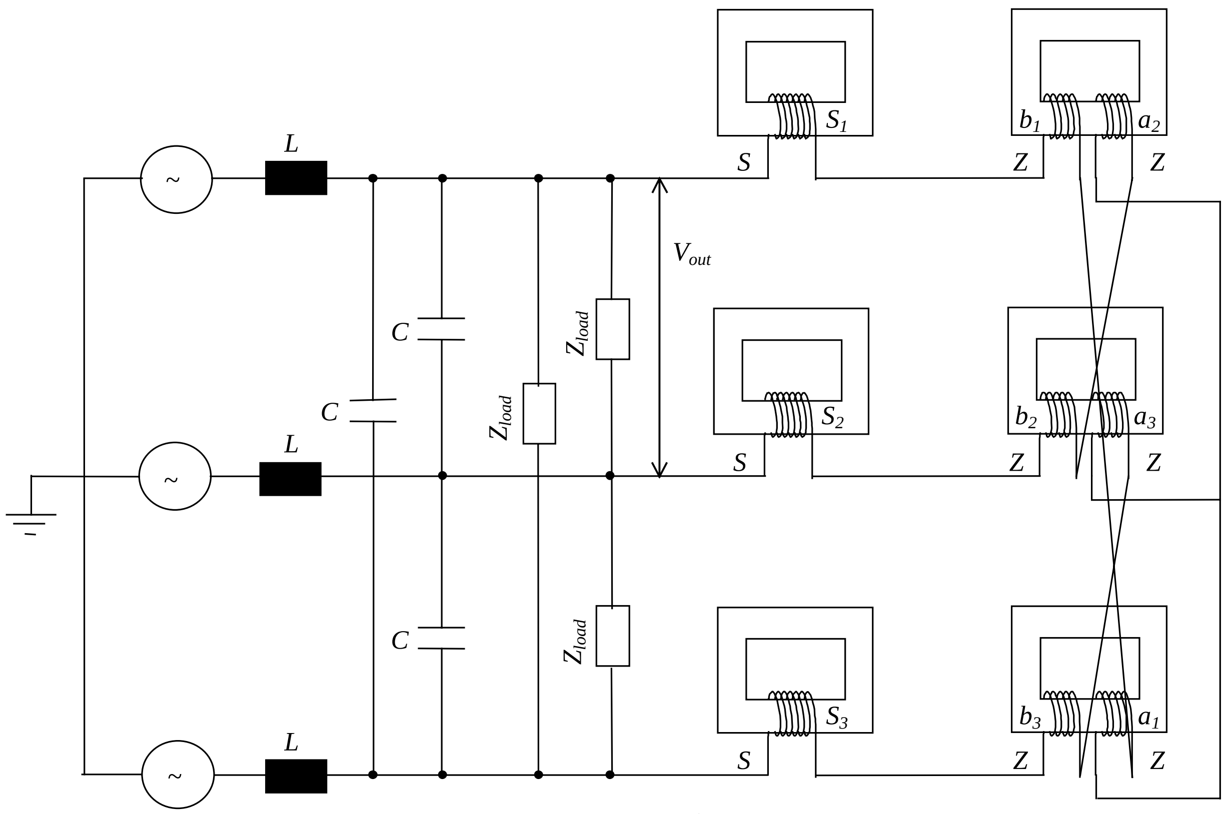

Fig. 1: Operating principle of a three-phase CVT

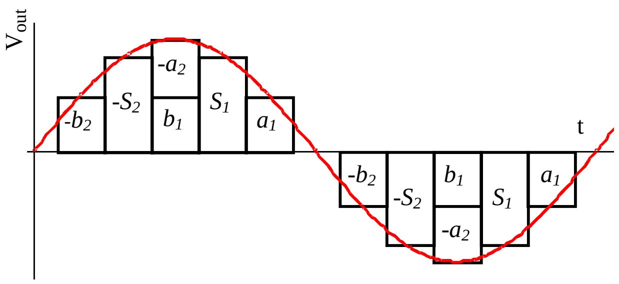

Fig. 2: Synthesis of sinusoidal voltage

MODELLING THE CVT

Computer simulations are necessary to evaluate the behaviour of the device under various conditions. Moreover, in the design phase they contribute in finding an optimal combination of design parameters, thereby reducing the need for expensive sets of prototypes.

The first step in modelling consists in the derivation of a set of general design equations. These were derived starting from similar equations for a single-phase CVT (3). Only the client specifications, such as rated voltage and power, and the required operational range have been considered fixed. The design parameters have all been expressed as functions of these specifications. Some iterations are needed to fulfil all requirements simultaneously.

The calculations are based on the instant where the three-phase constant-voltage transformer reaches its working area. A factor k is defined as the ratio between output and input voltage at the beginning of the working area.

$$k = \frac{V_{out,\min}}{V_{in,\min}}$$

For simplicity, the minimum output voltage $V_{out,\ min}$ is assumed to be equal to the rated output voltage $V_{out\ N}$.

$$V_{out,\min} = V_{out,N} = V_{out} = \frac{\hat{V}_{out}}{\sqrt{2}}$$

First, the characteristics of the nonlinear inductors are calculated. Figure 2 shows that the constant amplitude $\hat{V}_{out}$ of the output voltage is composed out of two voltage blocks from two windings Z on the same magnetic core. Assuming that the flux changes linearly in the time span of 1/12 of the period T from $-\varphi_{max}$ to $+\varphi_{max}$ (or vice versa), the Faraday law leads to following equation for the number of turns N_Z:

$$N_Z = \frac{\hat{V}_{out} \cdot (T/12)}{4 \cdot \varphi_{\max}}$$

For the calculation of the capacitor, the 3 nonlinear inductors of each phase are replaced by one equivalent nonlinear inductor L_{eq} per phase. The circuit behind the

3 linear inductors is being replaced by an equivalent complex impedance Z, characterised by:

$$\frac{1}{|Z|} = \sqrt{\left(\frac{1}{R_{load}}\right)^2 + \left(\omega \cdot C - \frac{1}{\omega \cdot L_{eq}} - \frac{1}{\omega \cdot L_{load}}\right)^2}$$

Assuming that the three-phase constant-voltage transformer has a 100% efficiency, $1/|Z|$ can be replaced by

$$\frac{1}{|Z|} = \frac{k \cdot \cos\varphi_{out}}{|Z_{load}| \cdot \cos\varphi_{in}}$$

In this formula, $\cos\varphi_{out}$ and $\cos\varphi_{in}$ are the power factor at the load, and at the input of the CVT respectively, on the instant that the CVT reaches the beginning of the working area. Using the previous equations, a final formula for C can be derived.

$$C = \pm\frac{1}{\omega} \cdot \sqrt{\left(\frac{k \cdot \cos\varphi_{out}}{|Z_{load}| \cdot \cos\varphi_{in}}\right)^2 - \left(\frac{1}{R_{load}}\right)^2} + \frac{1}{\omega^2 \cdot L_{eq}} + \frac{1}{\omega^2 \cdot L_{load}}$$

The solution with the + sign is the only one which is physically possible.

The last important parameter to be calculated, is the value L of the linear inductor at the input of the CVT. Observation of the phasor diagram of the CVT leads to a quadratic equation with unknown variable L.

$$V_{out}^2 = V_{in,\min}^2 + 3 \cdot \omega^2 \cdot \frac{3 \cdot V_{out}^2}{|Z|^2} \cdot L^2 - 3 \cdot 2 \cdot \frac{V_{\text{in,min}}}{\sqrt{3}} \cdot \omega \cdot L \cdot \frac{\sqrt{3} \cdot V_{out}}{|Z|} \cdot \sin\varphi_{in}$$

Replacement of $1/|Z|$, as done in the calculation of C, results in the final equation for L:

$$L = \frac{|Z_{load}|}{3 \cdot \omega \cdot k \cdot \cos\varphi_{out}} \cdot \left(\pm\cos\varphi_{in} \cdot \sqrt{1 - \left(\frac{\cos\varphi_{in}}{k}\right)^2} + \frac{\sin(2 \cdot \varphi_{in})}{2 \cdot k}\right)$$

Again, the solution with the + sign must be chosen.

A computer model for the simulation of the electric and magnetic variables can then be set up and implemented in a software package. For the application we chose for SPICE because of its flexibility, generality and user-friendliness.

Special care has been devoted to the modelling the magnetic material and the losses in the circuit. Essential for a realistic model is an accurate representation of the nonlinear characteristic of the magnetic core, made up out of thin iron sheets to reduce eddy current losses. Small unavoidable air gaps have a major influence on the magnetic behaviour. The good operation of the CVT requires a sharp transition at the knee-point and a flat saturation characteristic. These requirements can be obtained by choosing the appropriate magnetic material and core design. In this way, the behaviour of the core, including the small air gaps, approaches the characteristic of a single sheet of the magnetic material as good as possible.

A magnetic reluctance model, in which the influence of the air gaps is taken into account, has been used to determine the nonlinear magnetic characteristic of the core. A piecewise linear approximation has been used in the numerical model of the CVT.

The losses in the capacitors and the linear inductors can be approximated by including loss resistors. The losses in the iron core however, heavily depend on the magnetic flux, and can not be represented by a constant resistor. The results shown further in this paper neglect these iron losses, leading to an underestimation of the system losses. It will be shown that, though important for the overall efficiency, the effect on the waveforms is negligible.

REDUCED POWER PROTOTYPE

Using the design formulas, a prototype of reduced power has been developed. For practical reasons a transformer ratio of 1/1 was chosen. Table 1 summarises the data of the prototype, and figure 3 represents the final set-up. This picture includes the saturable inductors on the left hand side, the linear inductors on the right hand side, and the Δ-connected capacitor-bank in the front.

QUANTITY	VALUE
rated input voltage $V_{in,N}$	380 Vrms
rated output voltage $V_{uit,N}$	380 Vrms
max. input voltage dip	27.5 %
min. input voltage	275.5 Vrms
rated power S_N	2.177 kVA
linear inductor L	143 mH
capacitor C	31.617 µH
rated load R_{last}	227 Ω
number of turns N_S	230
number of turns N_Z	133

TABLE 1 – Prototype characteristics

Fig. 3: Three-phase CVT prototype

The parameter values of Table 1 have been introduced in the SPICE-model to compare experimental and numerical results, as shown in the following paragraph.

SIMULATIONS AND MEASUREMENTS

Rated load conditions

The behaviour of the three-phase CVT has first been studied at rated load with the input voltage as parameter. Fig. 4 shows the phase-to-phase output voltage and the current as a function of the input voltage. All electrical values shown in the different figures, are peak values. The rated point is situated at an input voltage of 537.5 V_{peak}, or 380 V_{rms}. The prototype has been designed in such a way that the output voltage remains constant from an input voltage as low as 275.5 V_{rms}. The graphic clearly shows that this requirement is met. Moreover, it shows the excellent agreement between the experimental measurements and the numerical results.
The voltage behaviour can be explained as follows. At low voltages, the system is perfectly linear and the output voltage rises proportionally with the input. When the cores saturate, the output voltage remains relatively constant since the amplitude of the blocks in fig.2 is determined by the flux variation. The line current also proportionally increases during the linear period. Going into saturation, the capacitors and inductors slowly approach the resonance condition where the current reaches a minimum. The current maximum at the left can be considered to indicate the lower boundary of the working region.

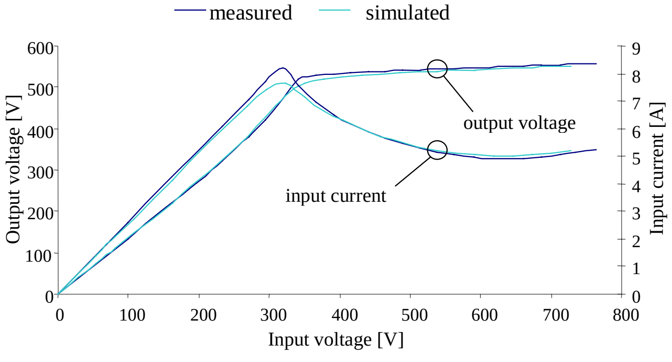

Fig. 4: Current and voltage at rated load

The power factor measured at the terminals of the CVT should preferably be close to 1. Figure 5 shows that the power factor is relatively good in the operational range; under rated conditions its value is 0.95.
The efficiency of the CVT is of course highly critical when evaluating its merits and drawbacks. The prototype which has been constructed, however, was not primarily developed with emphasis on efficiency.

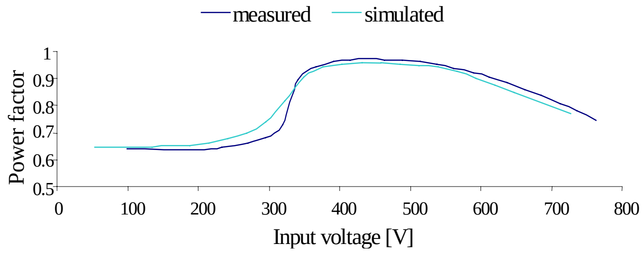

Fig. 5: Power factor at rated load

Therefore, the rather low figures are not representative for a full scale CVT, and different improvements in design and individual components are possible to increase the total system efficiency.
The conclusion when comparing measurements and simulations (figure 6), is that the agreement is acceptable in the operational range. At higher voltages, the differences between measurements and simulations become larger, due to the neglect of the iron losses.
In the design of a CVT, input voltage range and efficiency turn out to be two conflicting requirements. The maximum efficiency is reached at the start of the operational range. For higher input voltages, there is a slow efficiency decline. A large range inevitably causes a lower rated efficiency. To limit this reduction, the components should be chosen with care.

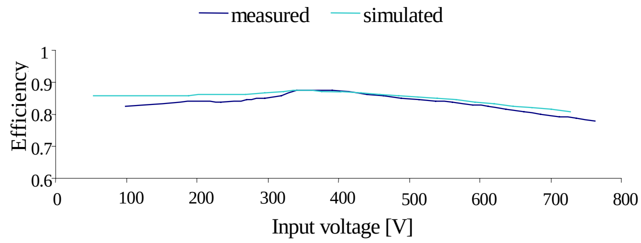

Fig. 6: Efficiency at rated load

Table 2 summarises the numerical values of the most important quantities for three values of the input voltage: the lowest voltage of the range (72.5%), the rated voltage and an overvoltage of 135%. The output voltage in this range varies between –2.1% and + 1.9%. The total harmonic voltage distortion in this range is situated between 1 and 2%.

V_{in} *rms*	275.5 V	380 V	513 V
V_{in} *peak*	390 V	537.4 V	725.5 V
V_{in} *% deviation*	-27.5 %	0 %	+35 %
V_{out} *rms*	376.8 V	385 V	392 V
V_{out} *peak*	532.9 V	544.2 V	554 V
V_{out} *% deviation*	-2.1 %	0%	+1.9 %
$Cos\varphi_{in}$	0.963	0.952	0.8
η	88 %	84 %	79 %
THD	0.8 %	1.4 %	2.1 %

TABLE 2 – Prototype results

Off-rated load and unbalanced conditions

The rated load calculated with the design formulas is a border value. For smaller resistances the output voltage will not remain constant with varying input voltage. This can be explained by considering the larger power demand for smaller resistances. At a given value, the normal resonant conditions are no longer met and the system is no longer able to stabilise the output voltage.
The CVT has also been evaluated for unbalanced loads. Measurements and simulations show that unbalances have little influence on the output voltage, as long as the system can maintain the resonant conditions. Only when the equivalent resistance decreases below the border value, the corresponding output voltage will collapse.
Even when one of the phases of the supply fails (e.g. after a short circuit in the grid), the three-phase CVT continues to deliver acceptable output voltages. This can be explained by the coupling between the phases, which is realised by the zigzag connected windings. In figure 7 the evolution of the phase-to-phase voltages is represented. Phase V fails at 0.03 s. After a short transient, a new steady state is reached. The three-phase voltage at the load terminals is no longer perfectly sinusoidal, but the load can remain supplied without interruptions. By placing appropriate filters the waveforms can be improved significantly, when necessary.

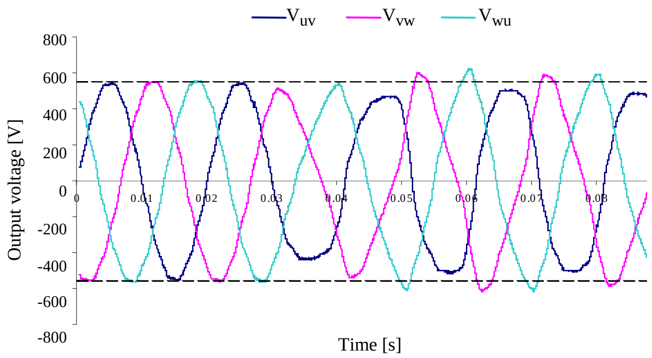

Fig. 7: Two-phase supply of CVT

FURTHER RESEARCH

A galvanic isolation may be needed and therefore, the functions of maintaining a constant voltage on the one hand, and transforming the voltage to a higher or lower level on the other hand, may be split between a CVT and a distribution transformer. The effect of this isolating transformer on the operation is limited.

The next step would be the design of a full scale 400 kVA CVT. The efficiency of the CVT increases with rated power and can be well above 99%. Maximum harmonic voltage distortion is limited to 2%. A cost analysis is imperative to investigate the economical feasibility of this project.

CONCLUSIONS

The three-phase constant voltage transformer supplies an output voltage with nearly constant amplitude over a wide range of input voltages. The total harmonic distortion is limited and unbalanced loads can be supplied without operational difficulties. These useful properties have been shown, both by means of numerical simulations based on a model implemented in SPICE, as well as by the construction of a small power prototype.
The agreement between simulations and measurements is excellent. Calculations for a higher power CVT show that this device may become an alternative for other solutions to power quality problems, since the positive voltage stabilising properties can be combined with a good overall efficiency. Besides, the developed computer model proves to be an invaluable tool to optimise the design of the CVT.
A lifecycle cost analysis will have to prove the economic viability of the series production of CVT's for low and medium voltage applications.

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