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A2 - Power Transformers and reactors
PS1 / EXPERIENCE AND NEW REQUIREMENTSFOR TRANSFORMERS FOR RENEWABLEGENERATION

Design of a 24-pulses 250 Mvar Thyristor Controlled Transformer

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SUMMARY

The continuously accelerating decarbonization process poses new challenges in terms of reactive power compensation; because of the coal power plant phase outs, less synchronous generators are expected to be in service on the 400 kV Italian transmission grid: both the National Energy Strategy (SEN) [1] and the "Comprehensive National Energy and Climate Plan" (PNIEC in Italian) [2] impose the complete phase-out of coal-fired power plants in 2025. Consequently, Terna (the Italian Transmission System Operator) is installing different reactive power sources, both for steady state (capacitor, shunt reactors) and dynamic (synchronous condensers, STATCOMs) for performing voltage regulation [3].
The installation of Synchronous Condensers (SCs) and STATCOMs is not, unfortunately, always a viable solution, due to high costs, and large footprint.
Terna's standard shunt reactors (400 kV / 258 Mvar) have a smaller footprint and reduced cost, if compared to SCs and STATCOMs. They are equipped with on load tap changer, for varying the reactive power output from 180 to 258 Mvar; however, they cannot perform dynamic voltage regulation and power oscillation damping: their response time is dictated by the On Load Tap Changer (OLTC) drive, so that the output can be varied from the minimum to the maximum operation point in about 1 minute taking into account only the mechanical manoeuvres.
Space availability in existing substations and long authorization times for SCs and STATCOMs thus forced Terna to examine different solutions for reactive power compensation, to reduce the footprint and the delivery times.
One of the main drivers for this project is the need for an asymmetric capability: in fact, as many Extra High Voltage (EHV) lines of the National Transmission Network are generally operated below the Surge Impedance Loading, a significant reactive power surplus is expected.

Under this regard, Static Var Compensators (SVCs) [6] have a significant advantage over SCs [4] and STATCOMs [5] [7], as they can be designed with an arbitrarily asymmetric capability curve. However, the SVCs footprint is relevant, especially due to the filters.
Terna thus evaluated, the installation of Thyristor Controlled Transformer (TCT). TCT represent a variant of SVC/TCR (Thyristor Controlled Reactor): instead of using a separate Step-Up transformer and linear air-core reactors, the transformer is designed with a very high leakage reactance, and the secondary windings are directly short-circuited through the thyristor controllers.
Aiming at a rated power of 250 Mvar, for eliminating the need for filters, Terna and Tamini defined a 24 – pulses configuration. Single phase design has been chosen, to overcome transport constraints. Advantages and disadvantages of different winding connection schemes have been considered, also taking into account losses and current harmonics cancellation.
The paper deals with the analysis and the design of a 24-pulses, 420 kV - 250 Mvar TCT, which, to the authors' knowledge, should be the largest unit of this kind.
In particular, the paper deals with the general characteristics of the TCT, the behaviour and characteristic harmonic emissions of an ideal TCT and the behaviour of a non-ideal TCT upon real operating condition, including non-characteristic harmonics.

KEYWORDS
Reactive power compensations, thyristor-controlled transformer, Static var compensator, STATCOM, Shunt reactors.

1. INTRODUCTION

TCT is a variant of the Thyristor Controlled Reactor (TCR); instead of using a separate step-down transformer and linear reactors, the transformer is designed with a very high leakage reactance, and the secondary windings are directly short-circuited through the thyristor controllers. A gapped core is necessary to obtain the high leakage reactance, and the transformer can take the form of three single-phase transformers.

Both 6-pulses and 12-pulses TCT topologies have been successfully adopted; however, when using these topologies, the need for filters has to be evaluated with regard to both characteristic and non-characteristic harmonics. In order to reduce the footprint related to the installation of filters, 24-pulses TCT topology has been chosen by Terna: the proposed solution is composed of four 6-pulses TCT, each supplied by a dedicated winding, with a phase shift of -22.5°, -7.5°, 7.5°, 22.5° (see Figure 1). Due to the transport constraints on the ageing Italian road/railway infrastructures, Terna adopted a single-phase design for the TCT project, whose main characteristics are reported in Table I. Each unit will be equipped with five winding: one EHV and four Medium Voltage (MV) windings. To attain the required phase shift, extended delta connection is adopted on MV windings [8].

TABLE I – MAIN CHARACTERISTICS OF SINGLE-PHASE POWER TRANSFORMERS.

EHV winding		***MV winding***	
U_r [kV]	S_r [MVA]	U_r [kV]	S_r [MVA]
400/√3	83.3	11/√3	20.8
230/√3	60	11/√3	15

U_r: rated voltage, S_r: rated power.

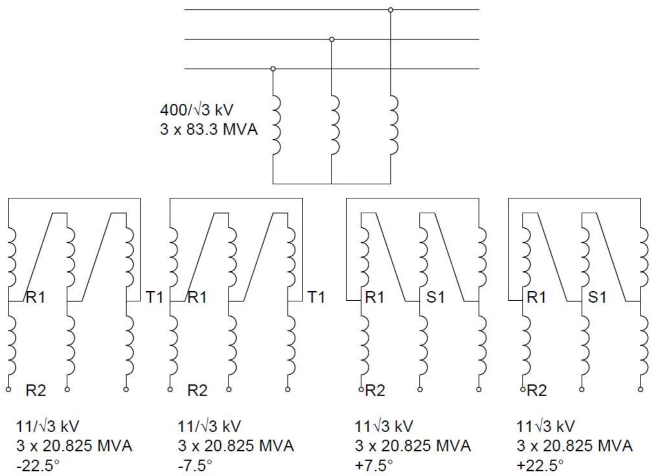

Figure 1 – Winding arrangements of the 24-pulses TCT single phase power transformer 400 kV/√3 / 11 kV/√3.

Considering the high value of rated reactive power of converter stations, 24-pulses TCT solution guarantees lower footprint if compared to Terna STATCOM projects. Indeed, ±125 Mvar Terna STATCOMs require 2 containers for control and auxiliary systems (2.5 m x 12 m) and 3 containers for valves housing (3.3 m x 13.7 m). Instead, a 250 Mvar 24-pulses TCT would require only 2 standard ISO containers (2.5 m x 12 m): each container contains both the control and auxiliary systems and thyristor valves for two 6-pulses converters.

The solution suggested by Terna allows to design a static compensation system with a higher reactive power density and lower cost and footprint if compared to standard commercial solutions such as STATCOM and SCs. If a capability in over-excitation is required, the installation of filters/condensers on the EHV busbars can be carried out.

2. BEHAVIOUR AND CHARACTERISTIC HARMONIC EMISSIONS OF AN IDEAL TCT

In this section the behaviour and characteristic harmonic emissions of an ideal TCT are carried out considering the equivalent circuit reported in Figure 2. The thyristor delta connection is adopted in the real TCT; for sake of simplicity, an equivalent delta circuit has been represented in Figure 2. However, the mathematical treatment can be straightforwardly applied to any winding connection scheme.

Each valve is made of two thyristors connected in anti-parallel arrangement; each valve is connected to different transformer bushings, thus short-circuiting two phases of a single transformer winding. Thyristor valve conduction causes the short circuit between two power transformer terminals and, therefore, the loading of power transformer windings. Power transformer is thus designed with a short circuit voltage equal to 100%. Due to the high short circuit impedances, power losses and, therefore, windings resistances can be neglected in the following mathematical treatment.

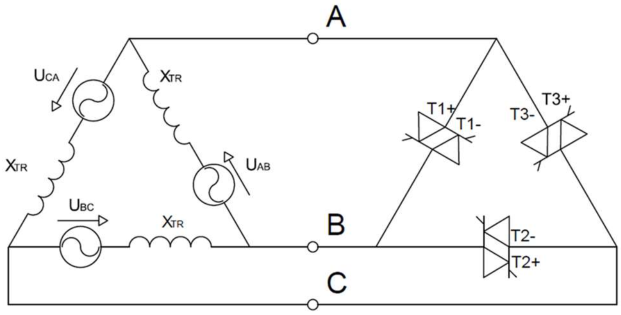

Figure 2 – Equivalent circuit of a 6-pulses TCT with secondary delta winding transformers.

Considering a symmetrical voltage source, the thyristor conduction angle σ is directly dictated by the firing angle α [7]:

$$\sigma = 2(\pi - \alpha) \tag{2.1}$$

Two thyristors of the same valve cannot be in the conduction state at the same time, due to their anti-parallel connection. However different valves, connected to different terminals of the same winding, can be contemporarily in the conduction state depending on the firing angle.

Taking into account (2.1) and a 120° shift between different phase voltages of the same winding, it is possible to identify three possible different operating behaviour:

1. First operation mode (full continuous conduction):
   for firing angles $\pi/2 \leq \alpha < 2\pi/3$ three thyristor valves, connected between different terminals of the same windings, are in conduction state at the same time. In this operation all the winding terminals are short circuited and reactive power cannot be modulated.
2. Second operation mode (reactive power modulation over two phases):
   for firing angles $2\pi/3 \leq \alpha < 5\pi/6$ two thyristor valves, connected between different terminals of the same windings, are in conduction state at the same time. In this operation either one or two valves are simultaneously conducting. Reactive power can be modulated over a significant range (from 100% to about 10% of the rated power)

3. Third operation mode (minimum reactive power, one phase):
   for firing angles $5\pi/6 \leq \alpha < \pi$ one thyristor valve is in conduction state. In this operation, only one valve conducts current at the same times. Reactive power can be modulated in a very limited range near to zero (from about 10% to 0% of the rated power).

As discussed above, the mathematical treatment regards the second and third operation mode of the ideal 6-pulses TCT. In the following, the mathematical equation of valve currents are reported in the time domains; the currents on the secondary and primary windings of the transformers can be evaluated starting with the valve currents and according to the winding connection schemes and turn ratio.

A. Second operation mode (reactive power modulation over two phases)

The valve currents and no-load secondary winding voltages of power transformer are reported in Figure 3, for a generic firing angle between 2π/3 and 5π/6. Considering the valve current between A and B terminals of power transformer, it possible to observe that:

- for $\alpha-\pi/2 \leq \omega t < 7\pi/6-\alpha$ the valve T_{1+} conducts with the valve T_{2-} connected between B and C terminals of the secondary winding of power transformer.
- for $7\pi/6-\alpha \leq \omega t < \alpha-\pi/6$ only the valve T_{1+} conducts.
- for $\alpha-\pi/6 \leq \omega t \leq 3\pi/2-\alpha$ the valve T_{1+} conducts with the valve T_{3-} connected between C and A terminals of the secondary winding of power transformer.

Considering the ideal behaviour of thyristor valves, the Thevénin Theorem can be applied between A and B terminals of secondary winding transformer, in order to evaluate the equivalent voltage and impedance:

$$\bar{U}_{th} = \begin{cases} \dfrac{\bar{U}_{AB} - \bar{U}_{CA}}{2} = \dfrac{\sqrt{3}}{2} U_{AB} \cdot e^{\left(j\frac{\pi}{3}\right)} & \forall\, \alpha - \dfrac{\pi}{2} \leq \omega t < \dfrac{7\pi}{6} - \alpha \\ \bar{U}_{AB} & \forall\, \dfrac{7\pi}{6} - \alpha \leq \omega t < \alpha - \dfrac{\pi}{6} \\ \dfrac{\bar{U}_{AB} - \bar{U}_{BC}}{2} = \dfrac{\sqrt{3}}{2} U_{AB} \cdot e^{\left(j\frac{2\pi}{3}\right)} & \forall\, \alpha - \dfrac{\pi}{6} \leq \omega t \leq \dfrac{3\pi}{2} - \alpha \end{cases} \tag{2.2}$$

$$\bar{Z}_{th} = jX_{th} = \begin{cases} j\dfrac{X_{TR}}{2} & \forall\, \alpha - \dfrac{\pi}{2} \leq \omega t < \dfrac{7\pi}{6} - \alpha \\ j\dfrac{2X_{TR}}{3} & \forall\, \dfrac{7\pi}{6} - \alpha \leq \omega t < \alpha - \dfrac{\pi}{6} \\ j\dfrac{X_{TR}}{2} & \forall\, \alpha - \dfrac{\pi}{6} \leq \omega t \leq \dfrac{3\pi}{2} - \alpha \end{cases} \tag{2.3}$$

being X_{TR} the short circuit reactance of power transformer seen from secondary windings.
Thus, neglecting losses, the valve current can be evaluated by integration of the following equation:

$$U_{th}(t) = L_{th} \frac{di_{AB}}{dt} \tag{2.4}$$

and therefore:

$$i_{AB}(\omega t) = \begin{cases} I_{p1} \cdot \left[\sin\left(\omega t - \dfrac{\pi}{6}\right) - \sin\left(\alpha - \dfrac{2}{3}\pi\right)\right] & \forall\, \alpha - \dfrac{\pi}{2} \leq \omega t < \dfrac{7\pi}{6} - \alpha \\ I_{p2} \cdot \left[\sin(\omega t) - \sin\left(\dfrac{7\pi}{6} - \alpha\right)\right] + I_{T1} & \forall\, \dfrac{7\pi}{6} - \alpha \leq \omega t < \alpha - \dfrac{\pi}{6} \\ I_{p3} \cdot \left[\sin\left(\omega t + \dfrac{\pi}{6}\right) - \sin(\alpha)\right] + I_{T2} & \forall\, \alpha - \dfrac{\pi}{6} \leq \omega t \leq \dfrac{3\pi}{2} - \alpha \end{cases} \tag{2.5}$$

with:

$$I_{p1} = \frac{\sqrt{2}U_{th}}{X_{th}} = \frac{\sqrt{6}\, U_{AB}}{X_{TR}} \tag{2.6}$$

$$I_{p2} = I_{p3} = \frac{\sqrt{2}U_{th}}{X_{th}} = \frac{3\sqrt{2}\,U_{AB}}{2X_{TR}} \tag{2.7}$$

$$I_{T1} = i_{AB}\left(\frac{7\pi}{6} - \alpha\right) = I_{p1} \cdot \left[\sin(\pi - \alpha) - \sin\left(\alpha - \frac{2}{3}\pi\right)\right] \tag{2.8}$$

$$I_{T2} = i_{AB}\left(\alpha - \frac{\pi}{6}\right) = I_{T1} \tag{2.9}$$

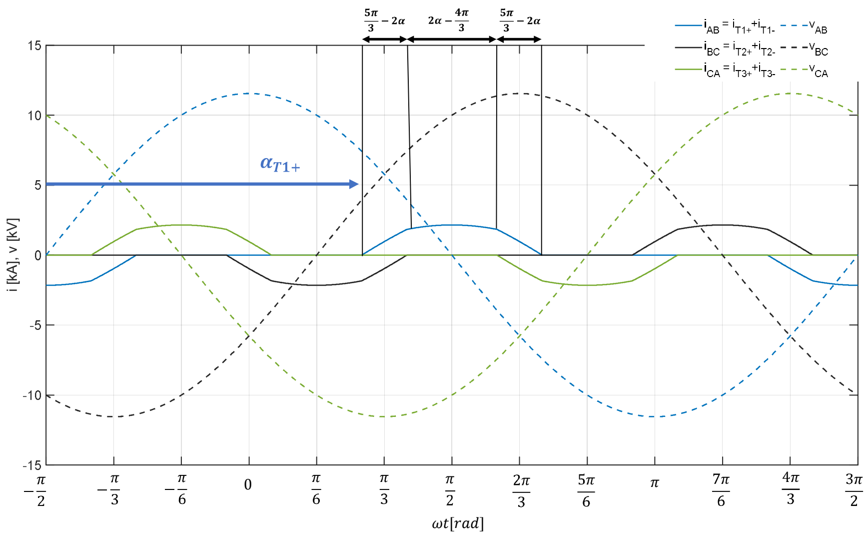

Figure 3 – Valve currents and no-load secondary winding voltages of power transformer for 2π/3 ≤ α < 5π/6.

B. Third operation mode (minimum reactive power, one phase)

The valve currents and no-load secondary winding voltages of power transformer are reported in Figure 4, for a generic firing angle between 5π/6 and π. Considering the valve current between A and B terminals of power transformer, it possible to observe that only one valve is in conduction state. The equivalent Thevénin voltage and impedance have been evaluated in the previous sections when only thyristor valve is in conduction state (i.e. for 7π/6-α ≤ ωt <α-π/6); therefore, the valve current can be evaluated according to the following equation:

$$i(t) = I_{p2} \cdot \left[\sin(\omega t) - \sin\left(\frac{7\pi}{6} - \alpha\right)\right] \tag{2.10}$$

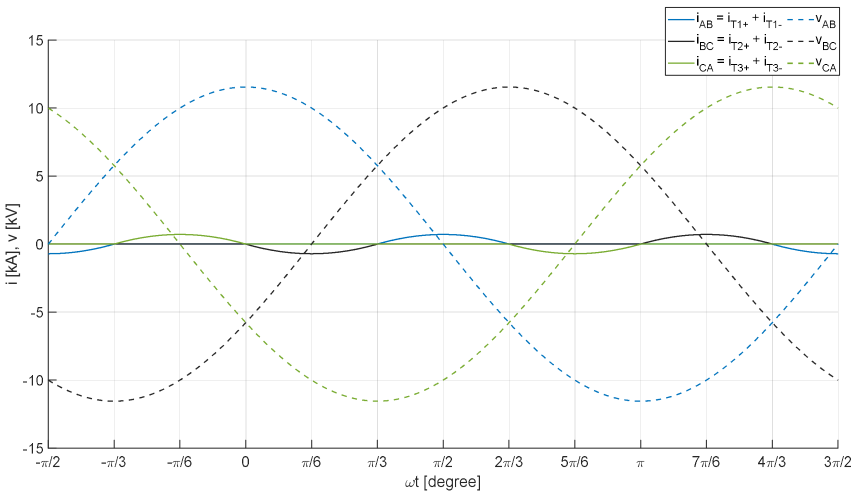

Figure 4 – Valve currents and no-load secondary winding voltages of power transformer for 5π/6 ≤ α < π.

C. Model validation using Alternative Transients Program (ATP)

The validation of the mathematical treatment has been performed using the software ATP – EMTP [9]; at first losses have been neglected as well as the thyristor deionization time and holding current (ideal valve). The valve currents for a firing angle equal to 140° have been evaluated both according to the mathematical treatment and ATP-EMTP simulation; simulation results, reported in Figure 5; evidence a perfect agreement between the mathematical treatment and ATP-EMTP simulations.

Using the same approach, the mathematical model of 12 and 24-pulses ideal TCT have been evaluated considering the appropriate turn ratio and winding connections of power transformer. Simulation results in time domain for a firing angle of 140° are reported in Figure 5.

For different firing angle, a Discrete Fourier Transformer (DFT) has been carried out in order to evaluate the harmonic content of a 6, 12 and 24-pulses ideal TCT; simulation results reported in Figure 6 evidence a perfect agreement between the mathematical treatment and ATP-EMTP simulation even in the frequency domain.

The reactive power in per unit of rated power has been evaluated as a function of firing angle for a 6-pulse ideal TCT; simulation results are reported in Figure 7 evidencing that the most of reactive power regulation can be performed between firing angle 120° and 150°. Figure 7 is applicable even for 12 and 24-pulses ideal TCT considering the appropriate rated power.

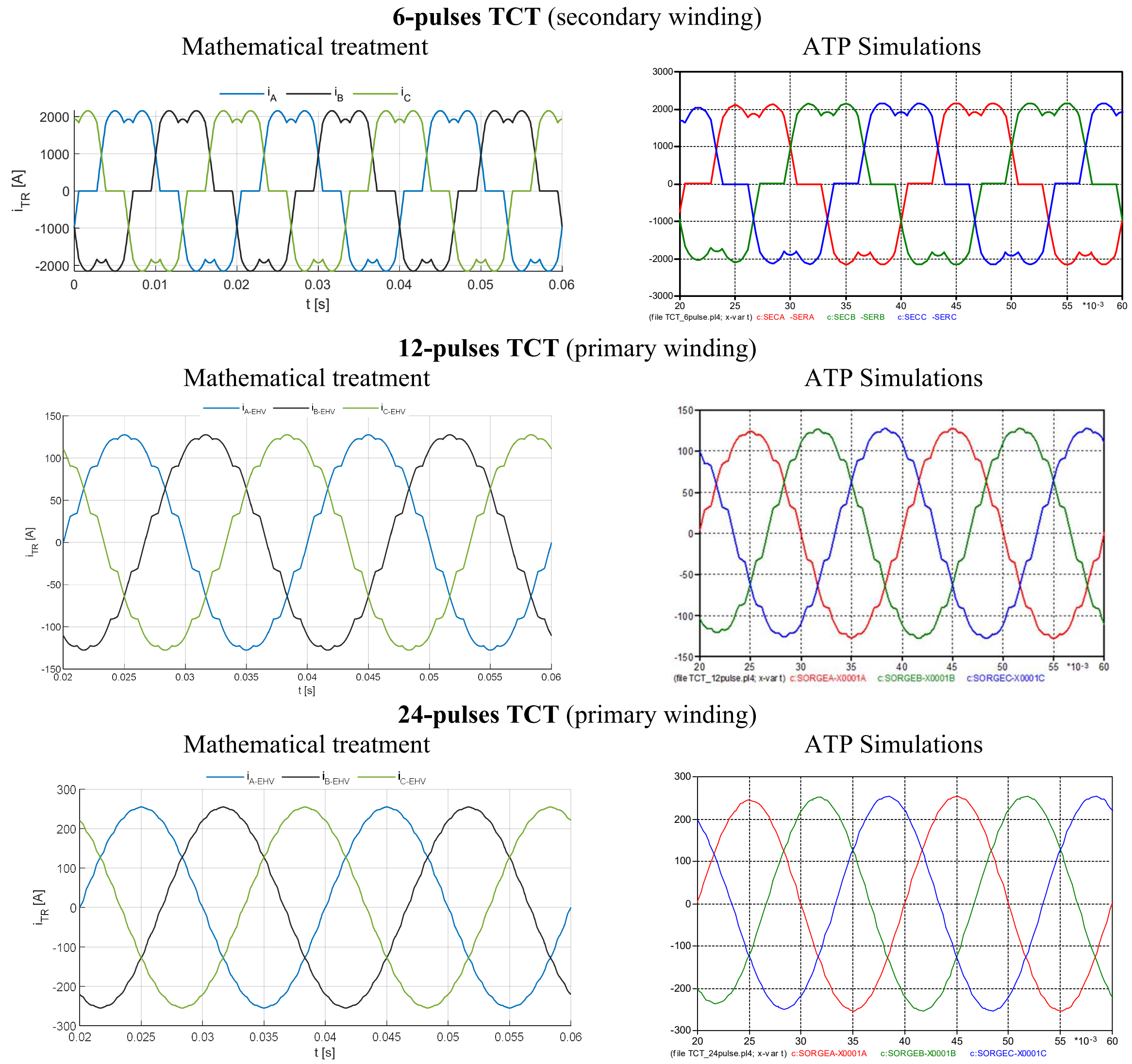

Figure 5 – Comparison of secondary/primary current of a 6, 12 and 24-pulses TCT for a firing angle α equal to 140° evaluated according to the mathematical treatment and ATP-EMTP simulations.

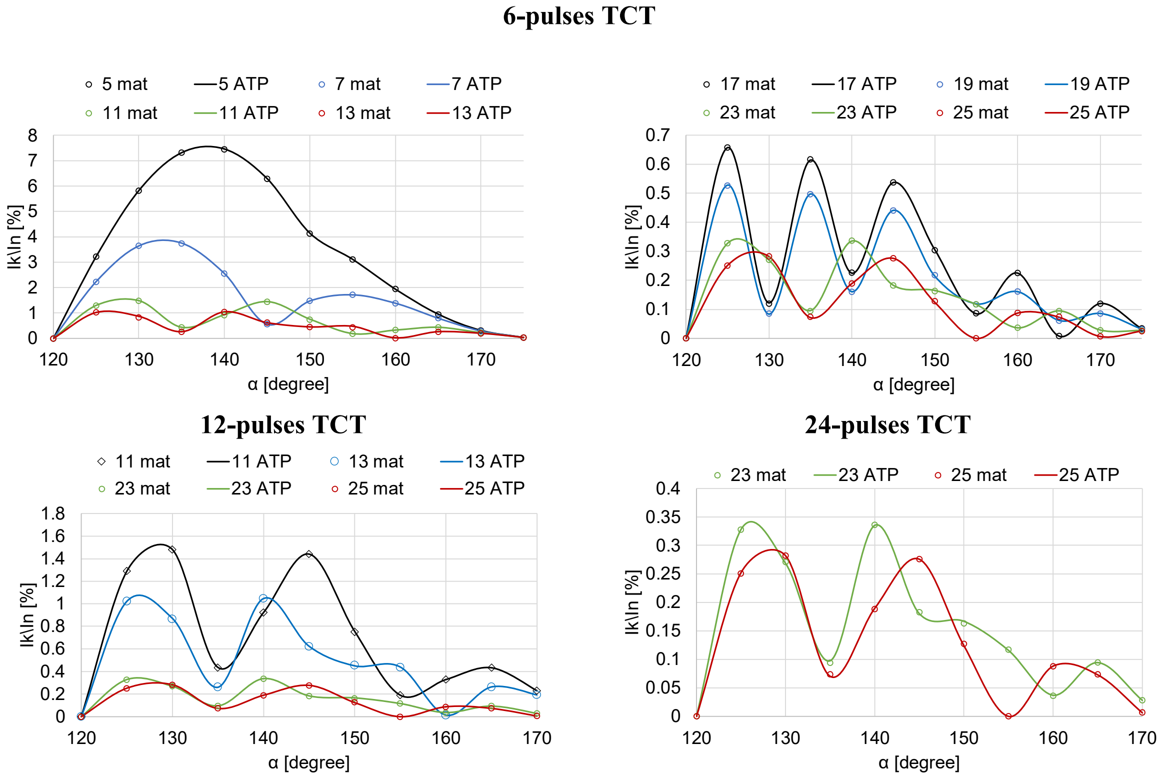

Figure 6 – Comparison of harmonic current content of a 6, 12 and 24-pulses TCT for a firing angle α equal to 140° evaluated according to the mathematical treatment and ATP-EMTP simulations.

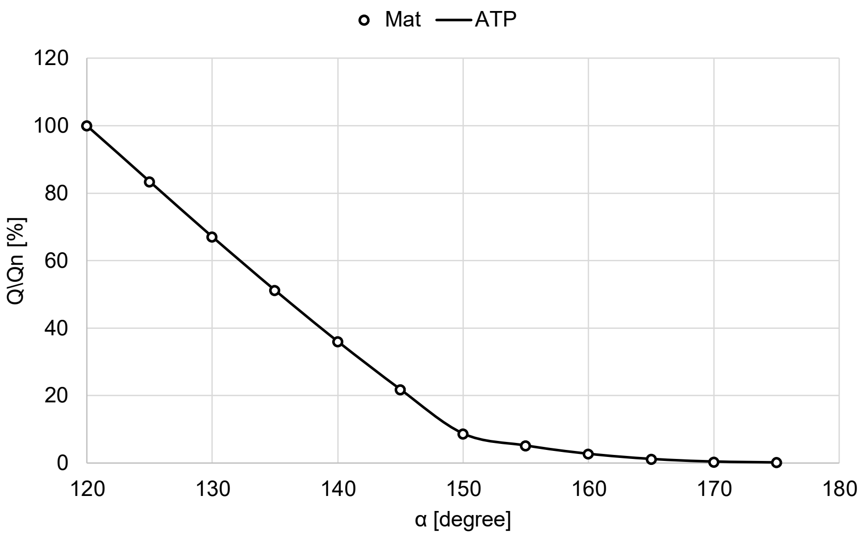

Figure 7 – Reactive power in per unit of rated power of an ideal TCT as a function of the firing angle.

3. BEHAVIOUR OF A REAL TCT UPON REAL OPERATING CONDITION

In order to evaluate the real behaviour of the 24-pulses TCT upon real operating condition, EMT simulations have been carried out with software ATP-EMTP according to the following assumptions:

- Thyristor valves have been represented with a Type 11 component of ATP software, considering both deionization time and holding current of commercial thyristor valves.
- For each 6-pulses TCT a dedicated firing circuit has been considered; each firing circuit has been developed in a Model-file of ATP software.
- Power transformer losses have been considered according to Terna requirements.

A sensitivity analysis has been carried out in order to evaluate the best strategy control of 24-pulses TCT in case of asymmetrical voltage supply; two possible Equidistant Pulse Control (EPC) strategies [10] have been developed:

- first strategy control: for all 6-pulses TCT only one EPC has been developed;
- second strategy control: for each 6-pulses TCT a dedicated EPC has been developed.

Simulation results evidenced that the EPC strategies applied for each 6-pulses TCT was the best strategy control in order to mitigate non-characteristic harmonic content. The firing circuit, implemented in software ATP, is represented in Figure 8; frequency supply (*f*) is evaluated with a Phase Locked Loop (PLL) [11]. For each firing circuit of 6-pulses TCT, the voltage reference (U_d) represented the positive voltage reference is evaluated measuring the voltage busbar at the EHV side (primary winding of power transformer) and shifted according to the secondary winding connection.

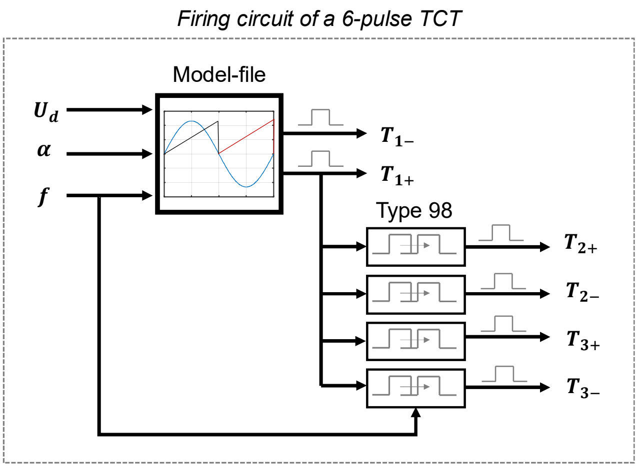

Figure 8 – Firing circuit of a 6-pulses TCT based on equidistant pulse control strategy.

A sensitivity analysis has been caried out considering several scenarios:

a) No-harmonic background content and symmetrical voltage supply (see Figure 9);
b) No-harmonic background content and 2% asymmetric of voltage supply (see Figure 10);

For each scenario harmonic current content generated by 6, 12 and 24-pulses TCT as well as Total Demand Distortion [12] have been evaluated; simulation results reported in the following figures evidencing that TDD of 24-pulses TCT is always lower than 1% in any scenario.

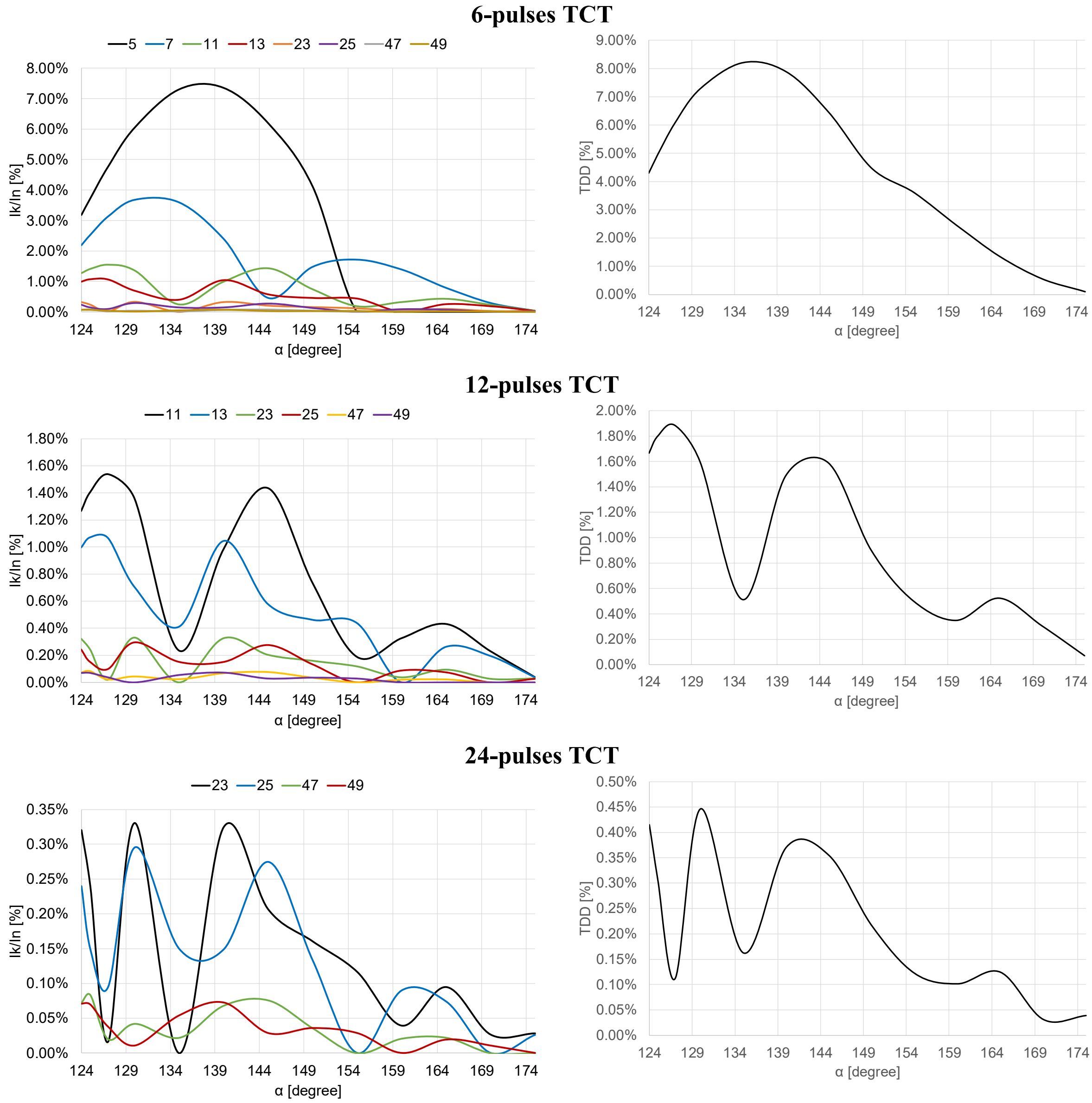

Figure 9 - Harmonic content and Total Demand Distortion of a 6, 12 and 24-pulses real TCT in per unit of the rated current without harmonic background content.

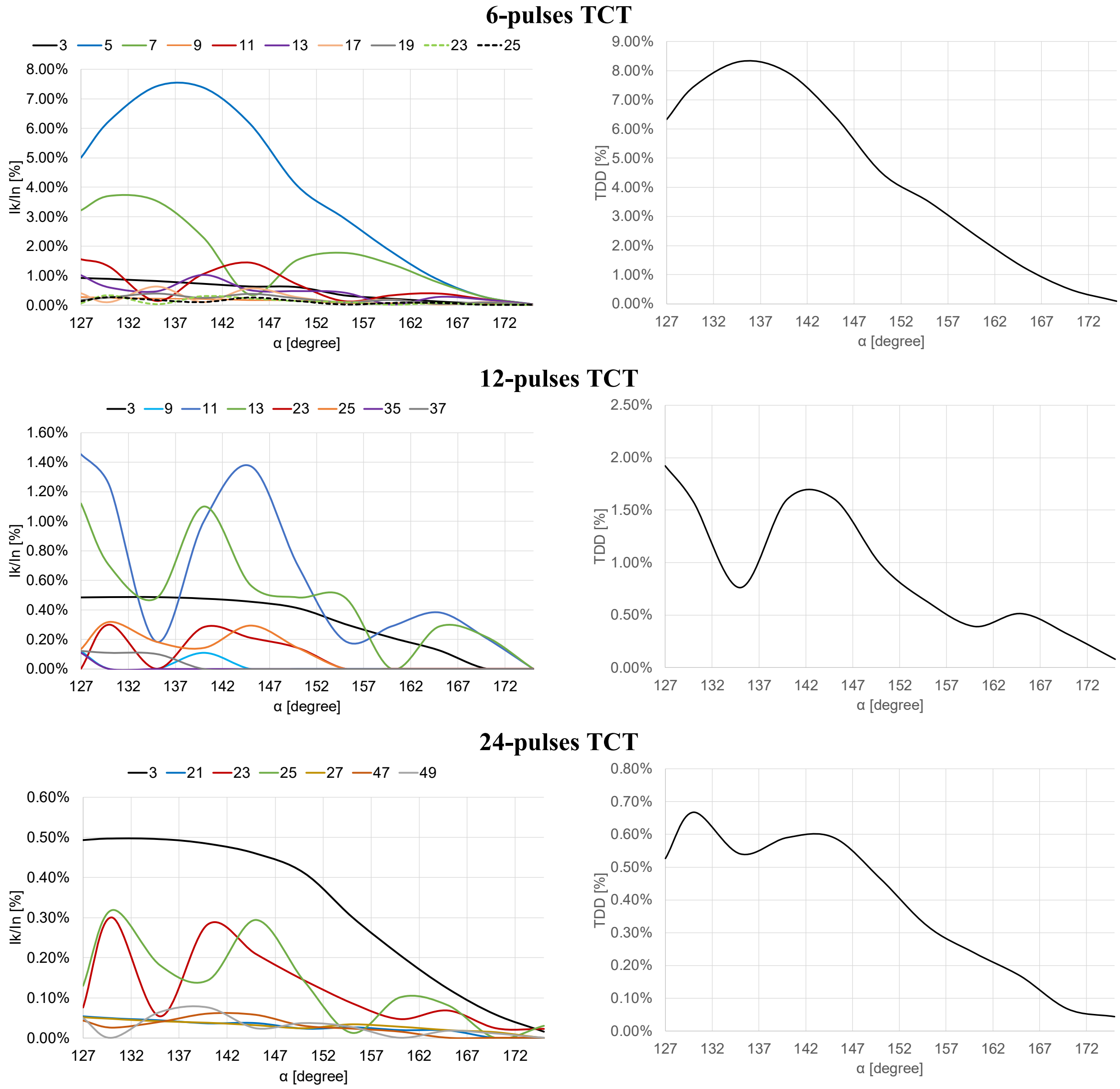

Figure 10 - Harmonic content and Total Demand Distortion of a 6, 12 and 24-pulses real TCT in per unit of the rated current without harmonic background content and with a 2% asymmetric of voltage supply.

4. CONCLUSIONS

Thyristor Controlled Transformers (TCT) represent an efficient solution for reactive power / voltage regulation, combining reduced costs and footprint with excellent dynamic performances and high expected reliability if compared to synchronous condensers and STATCOMs.
Its typical drawback, i.e. high current harmonic distortion, can be almost completely mitigated by using a more complex winding arrangement for the magnetic unit.
The paper presented a detailed evaluation of the harmonic performances for a 250 Mvar, 400 kV TCT to be installed on the Italian Transmission Grid, based on a 24-pulse arrangement.
Results evidence that the characteristic harmonics can be almost completely cancelled by increasing the number of pulses of the magnetic unit: upon ideal (balanced) operation the total demand distortion is lower than 0.5% using the 24 pulses configuration, much lower than the expected values for 6 or 12 pulses arrangements (8% and 2%, respectively). When taking into account the maximum expected voltage asymmetry (2% for the Italian 400 kV network), the total demand distortion is slightly increased to 0.67%, due to the presence of a negative-sequence 3rd harmonic current, but is still negligible and comparable to a modern STATCOM system.
Finally, time domain simulations, performed using a detailed model in ATP-EMTP, evidence a good agreement with the simplified theoretical treatment presented in the paper.

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