Abstract—In the paper some results of investigation of the single-phase transformer based AC pulse modulation mode regulated system of network voltage stabilization are presented. Switching processes in the device are regarded to application of transistor switches with proper snubbering circuits. Computer simulation as well experimental investigation of a model are done and its outcomes are presented.

I. INTRODUCTION

A problem for developing of fast-operating simple and reliable AC single-phase voltage stabilizer is really actual one. It is connected with Internationally accepted standards which allow variations of AC supply voltage in range +/-10% from the rated value (230V for the single-phase) of voltage level [1]. Thus electrical equipment is stressed by the higher meanings of voltage at the same time applying of higher voltages fosters in many applications rise of consumed power and decrease of efficiency. Therefore stabilization of the single phase AC voltage for customers is of high authority. Such stabilization devices must comply to some requirements – provide simplicity, cheapness, bi-directionality, to be reliable. Power ratings of stabilizers couldn’t be above some kW.

Such stabilizers can be developed on base of power electronic solutions – for instance it’s possible to realize double-stage conversion – rectifying with succeeding inverition on necessary output voltage shape and parameters. But devices of such type shouldn’t comply with requirements. It’s proposed to use direct PWM controlled converting [2,3,6] realizing bi-directional BUCK-BOOST operation on base of IGBT transistor application at application of the fast-operating sensors of the secondary voltage [4,5]. But anyway this solution is rather complex and asks for application of filtering devices [7] which rise as complexity as well cost of application.

In the last period have been proposed to apply systems where transformer is combined with semiconductor modulation tools [9,10,11]. Especially interesting is application of auto-transformers like devices which are characterizing with property when in case of small voltage variation range it’s possible to gain-through load power which can be much larger as transformer rated power [8,9,10]. For instance in [9] it’s shown that at 15% output voltage variation power of load could tenfold to be above one of an autotransformer’s. Supplementing such device with controllable electronic switches it’s possible to achieve stepwise change in small range a load voltage wave. At that simplest solution should be at application of only one secondary winding calculated for full load current and for BUCK case – contrary introduced regard to the separated by current ways the primary winding [9,10].

The task of this paper is more deeply investigate operation regimes of the such device – transformer based AC modulation system.

II. SCHEME OF THE DEVICE AND OPERATION PRINCIPLES

Let’s observe voltage regulation circuit which includes 2-winding transformer and 2 regulation transistors (Fig.1). Circuit is meant to compensate small range (up to 10%) voltage deviations above the rated one in network on constant impedance load which consists from resistor R and inductance L.

System works in following way: when load voltage is higher than needed, switch S2 is turned on (S1 off) and it connects the load to secondary winding w2, which is connected in respect to primary winding w1 in opposite phase. Primary winding w1 is constantly connected to supply voltage of the circuit.

![Fig. 1. Scheme of the transformer based AC modulation system accepted for investigation.](image)

Effective voltage of winding w2 is $U_2=U_1w_2/w_1=U_1/N$ and transformation ratio N is approximately 10, which would ensure compensation of $U_5$ rise on the load.

When voltage on the load is lower than needed, switch S2 is turned off and switch S1 - turned on. Switching process is implemented with constant and high enough frequency $f_m$, as well is controlled a switching duty ratio of switches S1 and S2 in constant switching cycle $T_m$ to achieve necessary output RMS voltage. If on-duty cycle for switch S1 is accepted as $D=t_1/f_m$, than simplified load voltage and network current waves in a k-th modulation interval can be shown as in Fig.2.
the k-th modulation interval, \( I \)

of transformer reduced to the secondary winding \( w \)

III.

SWITCHING PROCESSES AND ITS INFLUENCE ON OUTPUT PARAMETERS

Let’s consider switching process from the on-position of the switch S2 to the on-position of the switch S1 (see Fig.3). At the moment when the switch S1 is turned-on and the switch S2 – turned-off, the transient process starts in duration of which through the snubber capacitor \( C_{s2} \) of the switch S2 current \( i_2 \) of the winding \( w_2 \) of transformer passes and instantaneous meanings of current through the S1 in the very-short k-interval of supply voltage (modulation interval) wave can be find as difference of constant meaning of load current \( I_{lck} \) and decreasing to zero in the transient process current \( i_2 \). Duration of the process is accepted as \( t_k \) and at its end current of the switch S1 becomes equal to the \( I_{lck} \) and voltage of snubber capacitor \( C_{s2} \) – its maximum value for the k-th interval \( U_{C_{s2}k} \). Process depends on angular speed \( \omega_k=(L_{2TR}/C_{s})^{0.5} \) and wave impedance \( \rho_k=(L_{2TR}/C_{s})^{0.5} \), where it’s accepted that the both snubber capacitors are equally by its volume (i.e. to \( C_{s} \). Here \( L_{2TR} \) is a total leakage inductance of transformer reduced to the secondary winding \( w_2 : L_{2TR}=L_2+L_4 \).

The process can be described with expressions as follows: differential equation regard to the current \( i_2 \):

\[
-U_{2k} = L_{2TR} \frac{di_{2k}}{dt} + \frac{1}{C_{s2}} i_{2k} dt
\]

expression for the current \( i_2 \) change in the transient process

\[
i_{2k} = -\frac{U_{2k}}{\omega_k L_{2TR}} \sin \omega_k t + I_{lck} \cos \omega_k t
\]

expression for the current \( i_1 \) of switch S1 rise

\[
i_{1k} = \frac{U_{2k}}{\omega_k L_{2TR}} \sin \omega_k t + I_{lck} (1 - \cos \omega_k t).
\]

expression for calculation of duration of the transient process

\[
t_k = \frac{1}{\omega_k} \arctan \frac{I_{lck} \omega_k L_{2TR}}{U_{2k}};
\]

expression for calculation of the end value of snubber capacitor value in the process

\[
U_{C_{s2}k} = \frac{U_{2k}^2 - U_{2k} \sqrt{U_{2k}^2 + I_{lck}^2 \rho_{s2}^2 + I_{lck}^2 \rho_{s2}^2}}{\sqrt{U_{2k}^2 + I_{lck}^2 \rho_{s2}^2}}.
\]

When the switch S2 is turned-on but S1 – turned-off, then rise of current through switch S2 and current \( i_{2k} \) of transformer’s winding \( w_2 \) starts but in the way of transient a balance of currents, similar as in the first case, is in force.

Rise speed of current of the secondary winding in the transient interval depends on variations of voltage of the snubber capacitor \( C_{s1} \) of the switch S1 which should be described as

\[
L_{2TR} \frac{di_{2k}}{dt} = \frac{1}{C_{s}} \int i_{1k} dt
\]

As result at constant in the k-th interval load current, current of switch S1 is changing as

\[
i_{1k} = I_{lck} \cos \omega_k t
\]

but current of winding \( w_2 \) – as

Fig. 3. Diagrams of signals in the k-interval of network voltage wave.

\[
\]
Voltage of snubber capacitor $C_{lk}$ in the process changes as

$$U_{C_{lk}} = \frac{1}{C_s} \int I_{ldk} \cos \omega_k t \, dt = I_{ldk} \rho_k \sin \omega_k t$$  \hspace{1em} (11)

reaching its end value $U_{C_{lk}} = I_{ldk} \rho_k$ at time instant $\omega_k t = \pi/2$ when current $i_{sk} = 0$ but current $i_{2k}$ reaches its maximum value $I_{dk}$ (see Fig.3).

Rise of current in the winding $w_2$ at turn-on of the switch $S2$ is connected with self-inductance voltage generation in the inductance $L_{CTR}$. As result load voltage is decreased by this generated voltage in way of the transient process and this process can be described with equation

$$u_{ldk} = U_{sk}(1 - \frac{1}{N}) - L_{CTR} \frac{di_{2k}}{dt} =$$

$$= U_{sk}(1 - \frac{1}{N}) - \rho_k I_{ldk} \sin \omega_k t$$

where time interval is from 0 to $\pi/\omega_k$. At that largest instantaneous decrease of voltage is at instant, when $\omega_k t = 0.5\pi$ (see Fig.3). As result really realized load voltage in the time interval $(1-D)T$ is less as $U_{sk}(1 - \frac{1}{N})$ and should be considered with expression

$$u_{ld(1-D)k} = U_{sk}(1 - \frac{1}{N}) - I_{ldk} \rho_k \frac{\pi \cdot f_m}{2 \omega_k (1 - D)}$$  \hspace{1em} (13)

Taking into account decreasing of voltage in the intervals $(1-D)T$ and as well phase shift of the fundamental harmonic of load current $\phi = \arctg \frac{\omega_k L_{ld}}{R_{ld}}$ in respect to the load voltage wave, where $R_{ld}$ and $L_{ld}$ are respectively resistance and inductance of load, a wave of the fundamental of load voltage can be described with expression

$$u_{ld(t)} = U_{sm} \left( \frac{N - 1 + D}{N} \right) \sin \omega_k t - \frac{\rho_k \pi f_m}{z_{ld} 2 \omega_k (1 - D)} \sin(\omega_k t - \phi)$$  \hspace{1em} (14)

where $U_{sm}$ is the amplitude of supply voltage, $\omega_j$ is an angular speed for supply voltage wave, $z_{ld}$ is an impedance of the load.

As it can be seen a wave of load voltage is performed by two rotating phasors shifted by angle $\phi$ and the common phasor of load voltage can be obtained using subtraction of the second phasor dependant on the load current from the main phasor performed by modulation. At such approach the modulus of the common load voltage phasor is

$$U_{ld(t)m} = U_{sm} \left( \frac{N - 1 + D}{N} \right) \left[ 1 - \frac{\rho_k \gamma f_m}{z_{ld} \omega_k} + \frac{(\rho_k \gamma f_m)^2}{(2z_{ld} \omega_k)^2} \right]$$  \hspace{1em} (15)

and angle $\delta$ by which the fundamental of load voltage leads regard to the supply one – as

$$\delta = \arctg \left( \frac{\rho_k \gamma f_m \sin \phi}{(2z_{ld} \omega_k - \rho_k \gamma f_m \cos \phi)} \right)$$  \hspace{1em} (16)

IV. VERIFICATION OF SWITCHING PROCESSES AND ITS INFLUENCE ON OUTPUT PARAMETERS

For verification of processes a computer modelling have been done applying transformer of 50VA, winding’s ratio $w_1/w_2=8.33$, reduced to the secondary winding leakage inductance $L_s = L_1^* = 2.16mH$, resistance of windings $R_s = R_1 = 0.137 \Omega$, magnetizing inductance $L_m = 30H$ with load as $R = 100 \Omega$, $L = 50mH$ and transistor pulse modulator operating with modulation frequency $f_m = 1kHz$ at different duty ratios. In the table 1 some calculation results of process parameters for $U_{sm} = 340V$, $50Hz$ at applied duty ratio $D = 0.7$ of modulator with RDC snubbers comprising $C_s = 1 \mu F$ and $R_s = 50 \Omega$ as well obtained ones from computer modelling are presented.

<table>
<thead>
<tr>
<th>Name of the operating parameter</th>
<th>Calculated value</th>
<th>Simulated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS voltage of the load</td>
<td>229.4 V</td>
<td>226.0 V</td>
</tr>
<tr>
<td>Amplitude of load current</td>
<td>3.21 A</td>
<td>3.09 A</td>
</tr>
<tr>
<td>RMS of load current</td>
<td>2.26 A</td>
<td>2.2 A</td>
</tr>
<tr>
<td>RMS of supply current</td>
<td>2.14 A</td>
<td></td>
</tr>
<tr>
<td>Load voltage drop at turn-on of S2</td>
<td>96.1 V</td>
<td>97.5 V</td>
</tr>
<tr>
<td>Angular speed for snubber circuits</td>
<td>1.52.10^1/s</td>
<td></td>
</tr>
<tr>
<td>turn-on transient interval of S1</td>
<td>9.10^-5 s</td>
<td>8.8.10^-5 s</td>
</tr>
<tr>
<td>S1 snubber capacitor maximal voltage</td>
<td>166 V</td>
<td>154.9 V</td>
</tr>
<tr>
<td>S2 turn-on transient interval</td>
<td>1.03.10^-5 s</td>
<td>1.04.10^-5 s</td>
</tr>
<tr>
<td>S2 snubber capacitor maximal voltage</td>
<td>203.0 V</td>
<td>245.8 V</td>
</tr>
</tbody>
</table>

As it can be seen a compliance of the calculated and simulated parameters is rather good. Simulated diagrams of currents of switches and voltages of snubber capacitors at above mentioned parameters are presented in Fig.4 but diagrams of source and load voltages as well its currents are presented in Fig.5.
As it could be stated at experimental investigations a parameters of snubber capacitors must be coordinate with load power – for light power can be applied smaller volumes of capacitors, for stronger – bigger. From some viewpoints it should be drawback of applied system therefore more investigations regard to the problem must be done for farther developing of devices at different rate of power.

From the first view a leakage inductance of transformer windings at constant impedance voltage indicator is at reverse dependence on rated power of transformer. Therefore keeping relation $I_{ld}L_{2TR}/C_{s}$ as constant a choice of snubber capacitor volume should be directly proportional to the square root of transformer power rate.

V. CONCLUSIONS

1. The device can operate as stabilizer of load voltage below the level of supply network one with possibility to fluently change RMS value of voltage.
2. Switching processes in large extent depend on parameters of snubber circuits for transistor switches.
3. Calculation of switching processes can be done using obtained expressions which comply well with results of simulations and experiments.
4. Parameters of snubber capacitors applied depend on load power but the subject must be investigate more properly.

REFERENCES