Three-phase high overload DC power supply voltage with the mid frequency transformer ripple filter

JAROSLAV LOKVENC, RENE DRTINA, MILOS SOBEK
Department of Technical subjects
Faculty of Education, University of Hradec Kralove
Rokitanskeho 62, 500 03 Hradec Kralove
CZECH REPUBLIC
jaroslav.lokvenc@uhk.cz, rene.drtina@uhk.cz, sobek@vsh.cz; ktp.katedry.cz

Abstract: The study represents principle of three-phase DC power feeding source for high current consumption with a small ripple of output voltage. The feeding source is preferentially determined for industrial applications, in which slight fluctuation of output voltage with the change of the load does not matter, but the primary demand is high operation reliability, considerable overloading capacity and a small ripple voltage on the output of the feeding source. The described source uses mid frequency transformer compensation of output ripple and is composed exclusively of the passive elements.

This paper presents a new variant of DC voltage sources with high output current and transformer ripple filter. The DC power supply uses a three-phase full wave rectifier as a frequency multiplier power supply. The transformer is designed to filter the power supply frequency multiplied by six, and thus operates at a frequency of 300 (360) Hz. The document presents an analysis of the proposed solution and a detailed procedure for designing key parts of the power supply. Compared with conventional filters, our proposal uses a transformer with a DC saturation of the core without air gap.

Key-Words: Transformer, filter, power supply, noise voltage, ripple, overload, passive components, durability, reliability.

1 Introduction
The power supply is an integral part of every electrical and electronic equipment. Under the term is usually understood the power supply device that converts alternating current power grid to DC voltage. Output DC power supply is either stabilized or unstabilized, and has a certain proportion of noise signal (ripple). Just disturbing on the output voltage is a problem at power supply sources with high current sampling and variable load.

Connection of one-phase mains DC source with full-wave rectifier and transformer filter (1) could be applied with advantage for the area of supply currents in a number of tens, hundreds and thousands amperes in a variant of three-phase mains transformer with connecting bridge rectifier. Ripple on the output of the rectifier is than orderly smaller than in case of one-phase full-wave rectifier, where the disturbing part of rectifier voltage has the full amplitude between neutral and top voltage of rectifier voltage. Compensation transformer of ripple filter could be designed on selected magnetic core as a mid frequency, for smaller voltage, but for much more larger consumption currents. The main advantage of the source of this construction is a slight ripple in order of percentage and high reliability of the source, given by a small number of components. The source beside rectifier diodes is assembled exclusively from passive elements. The introduced solution represents significant lengthening of medium period of non-failure operation. In case of three-phase DC power source due to high demand currents, use of connecting linear serial stabilizer is not supposed. However application of the stabilizer at the source output is possible.

2 Existing solutions
The power three-phase mains sources of DC voltage with feeding transformer are constructed in historically steady connections, consisting from input transformer and rectifier even nowadays. Connection to the star (Y) on the secondary winding of the transformer is used with one-way (three-phase) or full-wave (six-phase) rectifier. (Fig.1, Fig.2) [2].
Basic filters of ripple could be then connected with rectifier. The filter with input capacitor (rectifier loaded with capacity) or filter with input reactance coil (rectifier loaded with inductivity) [1].

High duty DC switching sources represent modern solution of feeding circuits with relatively high efficiency. But they are circumferentially complicated and have relatively noise voltage on the output [3] and their disadvantage is, similarly as in the case of rectifier loaded, high current impulse at switching on and pulse character of the current drain from the mains network [4].

Next introduced scheme originates from the original study [1] and is suitable for feeding of electric appliances with high current consumption, to which does not matter decrease of voltage by influence of inner resistance of the source approximately about 10-15% (e.g. for starters of combustion engines). The main demand is small ripple of output voltage and high reliability of the feeding source, given by small number of devices. The source is designed for heavy conditions of industrial operations and agriculture, but its application in commercial sphere is not excluded.

### 3 Description of the function and scheme of the source

Until now unpublished schematic diagram of the source with the mid-frequency transformer ripple filter is shown in Figure 3. Input three-phase mains transformer TR1 in connection Yy is connected by primary winding $N_1$ (clamps U-V-W-N) to three-phase voltage $U_1$ with frequency $f$. The demanded value of voltage $U_2$ from separate winding $N_2$ of the secondary side is led on full-wave (six-phase) rectifier with $D_1$-$D_6$ diodes. Centre of the star of secondary winding is connected over the capacitor $C_2$, which symmetries run of the rectifier and blocks spurious transmission run at diodes commutation.

Rectified positive DC voltage with small-superimposed alternative part of voltage from the rectifier is transported on compensation transformer TR2 with ratio 1:1. Both winding of compensation transformer have the same number of $N$ turns and induction $L$. Primary winding of compensation transformer is connected alternative parts of pulse voltage, DC part goes over the secondary winding at the outlet of the source and load $R$.

Alternative part of secondary voltage is connected to series with primary voltage so, that the parts are mutually subtracted. Capacitor $C_3$ on the outlet of the rectifier decays transit overshoots at commutative diodes as primary induction $L$ of compensation transformer TR2 and capacity $C_1$ present for mains frequency series LC element adapted on under resonance frequency approximately 10-40 Hz. Therefore in case of source connection to mains, even two-times higher overshoot of voltage arises at capacitor $C_1$, which is decoyed with resistor $R_1$. It is possible for more significant limit of overshoot, in justified cases, use active limiter or $R$ load connected after
switching on of the source. Resistor $R_1$ guards minimal permanent consumption from the source about the size of approximately 1% of maximal current consumption, without it would occur charging of capacitor $C_1$ up to the top value of alternative voltage $U_2$.

The value of resistance load at the source output determinates in scheme optional current consumption between the values 0 up to $I_{\text{max}}$ and its value $R$ is considered in next calculations. By the effect of changing consumption and further effects (phase shifts on compensation transformer TR2) compensation of the altering part of rectifier quite ideal and ripple on the output of the source is usually bigger than the simple simulation models demonstrate. For more strict demands on output rifle, blocking capacitor $C_4$ is connected to the output clamps of the source, which decreases this rifle approximately about one order.

### 3.1 Method of source calculation and its connection

Calculation of this type of source is similar to the method given in [1]. But it differs in some steps of calculation, used equations and substituted values. The proposed method is again rather inspiratory must be completed with methods on calculation of heat loss, stress of separate devices and especially with method of source switching on, attendance of overshoot, etc. When calculation is done with help of computer, iteration calculus could be utilized. Compilation of the programme and its selectiveness is supposed in case of realization of industrial production and for sources of big output of tens and hundreds kW. In these cases it is necessary to solve even mutual power effect of the line wire and their mechanical realization. The design of the source is based on specification of desired values of the rectified DC voltage $U_{\text{DC}}$ at full load $I_{\text{DC}}$ and frequency $f$ of voltage distribution network (Table 1).

<table>
<thead>
<tr>
<th>symbol</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{\text{DC}}$</td>
<td>output voltage</td>
</tr>
<tr>
<td>$I_{\text{DC}}$</td>
<td>output current</td>
</tr>
<tr>
<td>$f$</td>
<td>frequency of power supply</td>
</tr>
</tbody>
</table>

Table 1 Specify the values of design

Taken DC power $P_{\text{DC}}$ is then calculated as

$$P_{\text{DC}} = U_{\text{DC}} I_{\text{DC}}$$

Power transformer TR1 must then be designed to $I_2$

$$I_2 = K_e I_{\text{DC}}$$

where we consider only three-phase full-wave rectifier ($K_0 = 0.816$) [2-5]. Then the angular frequency $\omega$ for line frequency $f$ is equal

$$\omega = 2\pi f$$

From diodes characteristics we determine their resistance $R_d$ for given consumption $I_{\text{DC}}$ and total resistance $R_i$ of the source. From equation (4) we determine needed secondary phase voltage $U_2$ of the first transformer (see DC device in (6)). And determine the top value $U_m$ of DC sinusoidal curve.

$$U_{\text{DC}} = \frac{3\sqrt{3}}{\pi} U_2 \cdot \sqrt{2} - R_d I_{\text{DC}} - R I_{\text{DC}}$$

and determine the peak value $U_m$ DC sine curve

$$U_m = U_2 \cdot \sqrt{2}$$

According to Fourier in the shape

$$U(\omega t) = \frac{3U_m \sqrt{3}}{\pi} \left( 1 - \frac{2}{5 \cdot 7} \cos 6\omega t - \frac{2}{11 \cdot 13} \cos 12\omega t - \frac{2}{17 \cdot 19} \cos 18\omega t - \ldots \right)$$

determine the amplitude of the sixth harmonic

$$U_{6\text{hm}} = \frac{3U_m \sqrt{3}}{\pi} \cdot \frac{2}{5 \cdot 7}$$

Other higher harmonics we do not consider, because their share is not significant. Efficient value of the sixth harmonic we determine as

$$U_{6h} = \frac{U_{6\text{hm}}}{\sqrt{2}}$$

Now the size of values of $L$, $C_1$, is chosen, when $L$ is the primary inductance of transformer TR2 (Table 2).
Table 2 Specify the values of filter

<table>
<thead>
<tr>
<th>symbol</th>
<th>value</th>
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</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>capacitor on the primary side of the filter</td>
</tr>
<tr>
<td>$L$</td>
<td>the inductance of the primary transformer TR2</td>
</tr>
</tbody>
</table>

If in later calculation some of the parameters are not satisfying, especially inequality (24) is not fulfilled, the choice of $L$ and $C_1$ must be repeated [1] with another values. If not satisfied inequality (24), the choice of the $L$ and $C_1$ repeated with other values. Further the resonant frequency $f_0$ of circuit $LC_1$ and fulfilling of above resonance operating with connecting condition.

$$f_0 = \frac{1}{2\pi\sqrt{LC_1}} \quad (9)$$

$$f_0 \leq \frac{2f}{3} \quad (10)$$

Here again, the previous consideration is applied, when necessary increase of the value of inductance $L$ is preferred to increasing of values of capacitance $C_1$. In addition, certain factor of filtration $k_f$ load of the sixth harmonic is determined as

$$k_f = 1 - \omega_1^2 LC_1 \quad (11)$$

Where the negative sign in the result means reversal of the phase and where for angular frequency $\omega_1$ is valid with regard to two-way three phase rectifying (three-phase bridge rectifier), that

$$\omega_1 = 12\pi f \quad (12)$$

If the power supply is loaded mainly with a maximum current, and depends on the exact size of the filtering load factor $k_f$, this can be more accurately determined from the equation

$$k_f = \sqrt{\left(1 - \omega_1^2 LC_1\right)^2 + \left(\frac{\omega_1 L}{R}\right)^2} \quad (13)$$

Efficient ripple value on the load $R$ is then

$$U_{RMS} = U_{ph} \cdot \frac{1}{k_f} \quad (14)$$

and has approximately sinusoidal course. The total load on the power supply output is

$$R = \frac{U_{DC}}{I_{DC}} \quad (15)$$

To prevent output voltage overshoot at power source, capacity of capacitor $C_1$ must have been

$$C_1 \leq \frac{L}{(2R)^2} \quad (16)$$

where $R$ is the total load resistance of the source. For practical realization is preferable to limit the transition operation after switching on a power source with other supplementary resources [1] and the size of $C_1$ capacity submit mainly to required size of filtration $k_f$ according to (11) or (13).

3.2 The principle of the design of the mid-frequency compensation transformer

Calculation design follows, which concerns determining of the parameters of the compensation transformer TR2. Core cross section of $S_{Fe}$ is in the first step chosen from a standardized series of cores (for example the core UI), most often the same or one level higher, as would be selected in the current design for power

$$P_{DC} = U_{DC}I_{DC} \quad (17)$$

Table 3 Specify the values of core

<table>
<thead>
<tr>
<th>symbol</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_r$</td>
<td>relative permeability</td>
</tr>
<tr>
<td>$l_s$</td>
<td>length of middle line of force</td>
</tr>
<tr>
<td>$S_{Fe}$</td>
<td>core cross-section</td>
</tr>
</tbody>
</table>

After selecting the core, from its table parameters $\mu_r$, $l_s$, $S_{Fe}$, the magnetic resistance $R_m$ is determined by the equation

$$R_m = \frac{1}{\mu_0 \mu_r} \cdot \frac{l_s}{S_{Fe}} \quad (18)$$

and for given inductance $L$ according to Table 2 even the number of turns $N$ in primary and secondary windings.
DC induction in the core of TR2 caused by power consumption $I_{DC}$ from the source, is then

$$B_{DC} = \frac{\mu_0 \mu_r N I_{DC}}{I_s}$$  \hfill (20)

Magnetizing current is then (we do not consider higher harmonics) given by

$$I_\mu = \frac{U_{sh}}{\omega I L}$$  \hfill (21)

This current produces in the core induction about effective value

$$B = \frac{\mu_0 \mu_r N I_\mu}{I_s}$$  \hfill (22)

Table 4 Specify the maximum induction in the core of compensation transformer TR2

<table>
<thead>
<tr>
<th>symbol</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{max}$</td>
<td>maximum induction in the core</td>
</tr>
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</table>

If we determine the maximum allowable value of flux density in the core $B_{max}$ (Table 4), the total peak flux density in core at full collection $I_{DC}$ given by equation

$$B_{TOT} = B_{DC} + B \cdot \sqrt{2}$$  \hfill (23)

Its size must fulfill condition

$$B_{TOT} \leq B_{max}$$  \hfill (24)

When it is not fulfilled the calculation is repeated by selecting a smaller inductance $L$ or by choosing a larger core (from equation (18)).

However, we often give priority to larger transformer TR2 value of primary inductance, to achieve greater filtering agents, and, it means that the compensation transformer is designed to supply a disproportionately greater than would be the effective value of the sixth harmonic.

On the contrary, excessive increase of the inductance means that the increasing number of coils disproportionately increases the internal resistance of the source or the size of the core. But at stationary sources this fact does not be a trouble. For decrease of diffusion induction of compensation transformer TR2 is suitable to realize both winding as bifilar one.

### 3.3 Feeding transformer TR1

The design of TR1 is usually done by standard methods for designing of three-phase transformer [2-4] (core - three-pillar transformer). Specific demands according to the operation condition of the source are taken into consideration in the design. With regard to presumed operation conditions the transformer is solved as an industrial type. Magnetic inductor in the core, due to demanded short time of overloading of the source, is chosen usually lower than maximal possible operation value, e.g. for standard transformer core of sheet metal UI with a maximum magnetic field $B_{max} = 1.3$ T, we select operation of magnetic induction $B = 1$ T to $1.2$ T.

### 3.4 Design of feeding source

Design of three phase feeding source with transformer of distribution voltage is realized in the framework of solving of research project PdF SV 10/2012. The aim of the research project is realization of the prototype of feeding source (according to the basic scheme in Fig.3) with output voltage 14.4 to 10.8 V at current demand 0 up to 120 A. With regard to interference load of the secondary part the source is designed in robust industrial realization. Transformers TR1 and TR2 are of core type, type of the used transformer-core-lamination UI. Traction diodes are used as rectifier SKKD162 (three half-bridges).

After basic calculations the design of the source was optimized by means of NI-Multisim 12. One of the entry requests for the design of source was minimal sub-transient current at switching on of the source, it is at the connection of TR1 to the feeding mains. With regard to it a mathematical model [5-9] of the transformer on the base of systems of differential equation [10] in cooperation with technology department of the firm BV Elektronik Holice.

Simulated wiring presumes permanent operation with 120 A consumption and a short time operation (in minutes) with consumption up to 140 A. The applied rectifier is able to deliver maximal current on the level of 270 A. The current peak is safely secured by it, e.g. at switching on of serial engines. In practice it is possible to consider with peak overloading up to the level of 100%.

Analysis of the filter function shown in Figure 4. Channel A shows the rectifier ripple output, channel B shows the ripple output of the filter.
Maximal output voltage of designed source is 14.4 V and it corresponds to safety operation parallel connected lead accumulator with the nominal voltage of 12 V. Compensation transformer TR2 acts at source switching to mains as a current inrush filter and decreases switching current peak in secondary circuit approximately to 50-70 A. Switching current peak is therefore also decreased in primary circuit of the transformer TR1 and standard protection element in mains for source protection is quite sufficient.

4 Conclusion

In spite of apparent simplicity of the power source connection with mid-frequency transformer compensation of current inrush we consider as useful to introduce detailed principal design of this type of source. It is case in the main differently damping serial LC-circuit with close transformation bound fed with ripple DC voltage. It is a simple reliable source determined especially for heavy operation conditions. Robustness of the source is given by application of two transformers does not mean burden at stationary installed sources for feeding DC SELV and PELV mains for low voltage current distribution of buildings or for traction use or electroplating.

We suppose that introduced principal design is a starting point for further applications and it could differ in separate steps according to the area of mid or big power outputs in industrial applications.

Exploitation of the source could be also supposed for start of combustion engines under difficult climatic conditions, especially in construction industry or agriculture, where stability of output voltage and its small ripple contributes to a steady run of DC engines, does not endanger the accumulator with passage of high current and it is not necessary to disconnect it at the starting.

References:


