Design of Transformer and Power stage of Push-Pull Inverter

Milomir Šoja, Slobodan Lubura, Dejan Jokić, Milan Đ. Radmanović, Goran S. Đorđević, and Branko L. Dokić

***Abstract*—In this paper is presented the example of construction of push-pull inverter that can be used in two different topologies, with two input voltages and three power ratings which can at the same time achieve AVR function and "power-save" feature. Special attention was paid to scheme, turn ratio calculation and transformer coil windings arrangements that with only two types (of different power ratings) allows realization of large number of push-pull inverter configurations that can be applied to different power supply systems.**

***Index Terms*—Over-voltage protection, Power stage construction, Push-Pull inverter, Transformer.**

I. Introduction

SINGLE-PHASE voltage inverters found their wide application in uninterrupted supply systems (UPS) for computers and computer-based devices and recently in power supply systems with renewable energy sources (sun, wind). In both cases inverters play the most important role, which is transformation of DC voltage (usually accumulator battery) to AC voltage that corresponds to power supply. Basic requirements for the devices that are used with such delicate application are: simplicity, reliability, efficiency and low price.

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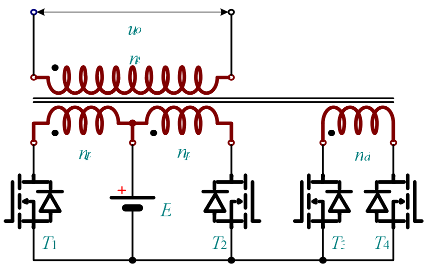
In cases when input DC voltage is low (12/24 V), and required inverter power relatively high (several kVA), the above mentioned requirements in both applications are satisfied to great extent typologies of push-pull (PP) inverters and two parallel push-pull (2PP) inverters with secondary transformers serially connected because of low number of components and low conduction losses. Output voltage of such inverters often has so-called "modified/quasi-sinus" wave shape that allows further increase in efficiency (minimum switch losses) as well as control according to the proposed criteria (usually regulation of effective value with required precision). [1]

Standard requirements for construction of power stage of inverter are: compactness, small dimensions, low weight, simple assembly and service. Besides these requirements there was a request that construction solution of inverter should be in such manner that both interest typologies (PP and 2PP) can be realized with simple configuration, that three typical power ratings can be achieved (0.5, 1 and 2 kVA) for input voltages 12/24 V, with the ability to achieve several variants of AVR (*Automatis Voltage Regulation*) function and "power save feature". [2] [3] [4] [6]

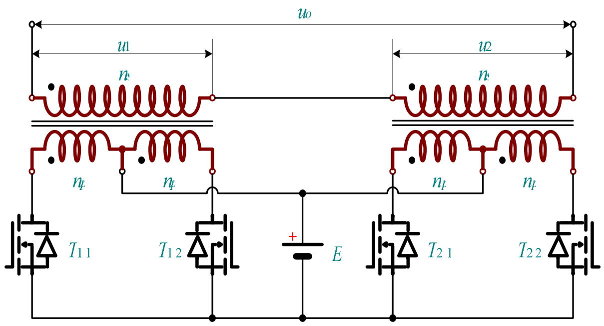
Because of its crucial importance for accomplishment of the above mentioned functions and its great influence on achieving the optimal constructing solution, special attention was devoted to the choice of scheme and calculation of transformer parameters. After the detailed analysis variant of transformer with eight windings and two power ratings (0.5 kVA (S_{500}) and 1 kVA (S_{1000})) was suggested. It allows all the interest variants of the device and it fits perfectly to the construction solution. [11].

II. INVERTER OUTPUT VOLTAGE

"Quasi-sinus" wave shape was chosen for inverter output voltage because it fully satisfies target consumers (computers and household devices), it allows minimal switch losses and it also allows control based on different criteria (minimal THD, basic parameters are the same as in the corresponding sinus signal, effective value is constant). Topologies PP and 2PP are shown in *Fig.* 1 and they are suitable for formation of voltage with "quasi-sinus" wave shape. Specificity of the presented PP inverter (*a*) is in the added reset winding of the transformer (n_d) and power semiconductors switches (T_3, T_4) which are necessary for formation of the required output voltage wave shape. With 2PP topology (*b*) "quasi-sinus" output voltage is achieved through voltage time shifts of individual PP inverters. Control was chosen according to the criteria that inverter output voltage effective value ($U_{o.ef}$) is constant, with limitation that impulse width(t_u) is always greater than certain minimal value ($t_u \geq T/4$), *Fig.* 2. [11].



a) PP inverter with added reset winding.



b) 2PP inverter.

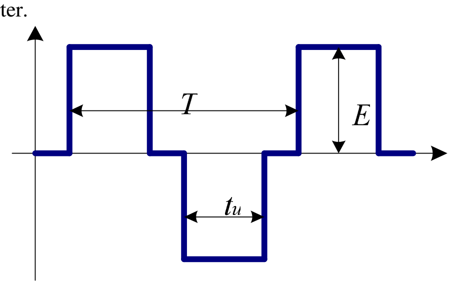


Fig. 1. c) Inverter output voltage.

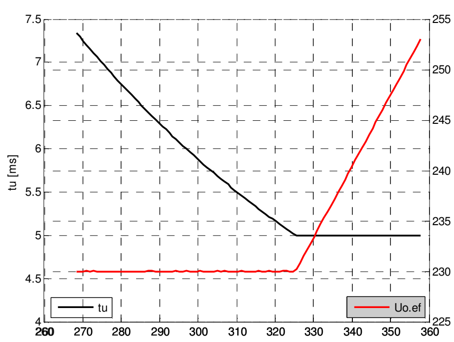


Fig. 2. Dependance of $U_{o.ef}$ i t_u from changes in secondary voltage for $t_u \geq T/4$.

As a consequence to the above mentioned limitation, in certain areas of change in input voltages there is no regulation of effective value of output voltage. In order to reduce that area we can influence it by the choice of working point used for calculating transformer turn ratio.

In other words, the choice of secondary voltage maximum value. If maximum value of transformer secondary voltage corresponds to the maximum voltage of accumulator (approx. 2.4 V/cell), problem of unregulated effective value is being mitigated because operating accumulator voltage/secondary voltage is significantly lower than the maximum, so it does not reach deeply into the restriction area t_u. When the maximum value of secondary voltage corresponds to accumulator maintenance voltage (approx. 2.3 V/cell), restriction period t_u is longer, and so the divergence of output voltage effective value is greater. The highest effective value is in any case within limitations from 1.1 $U_{o.ef.nom}$.

III. CONSTRUCTION OF INVERTER POWER STAGE

Satisfaction of construction terms demanded detailed analysis and calculation of all the components of the power stage as well as the methods and procedures required for the achievement of the optimal solution.

A. *Establishment of connections between power components*

One of the most important decisions in the construction of inverter power components is component assembly procedure or integration level. Our experience [6], but also manufacturer's experience [7] suggests that the base for construction should be double-sided printed circuit board (PCB) that is also used as component carrier, primarily for cooler, and medium for establishment of all electrical links between the components of the executive body.

PCB allows that the links between components are established in such manner that all the ways of current commutations are the shortest possible. Besides that, all the components that are necessary for switching on/off and protection of power switches can be positioned in the closest vicinity of the switches that additionally simplifies the assembly and increases reliability of the device. Besides the semi-conductive components and components necessary for AVR function and power save, it is also possible to place circuit and voltage measuring transformers and matching fuses on PCB. In that manner, the number of necessary conductors/wires is minimized, assembly of the power stage and its connecting to other device components is simplified to the maximum level and it can be performed by labor force with minimum expertise. Electrical and mechanical/ construction features of the device are improved, reliability is enhanced and cost is lowered.

PCB use for realization of inverter power stage also brings certain limitations. Because of its mechanical characteristics (flexibility, capacity) it is agreed that dimensions of PCB should not exceed 160x240 mm. Second serious limitation is maximum value of current that can be transmitted through printed connections. For the safety and reliability reasons and with regard to the available width of the connections it is estimated that total current in one PP should be limited to 50 A. It disabled the application of certain converter types at lower voltage and with greater power, mostly PP at 12 V. 2PP can be applied in all cases because of splitting of input power, except for 12 V, 2 kVA (*Table* 1.).

B. *Choice, protection and triggering the switch*

Choice of semi-conductive power switches and their security and triggering manner has crucial influence on operating quality, reliability and efficiency of the inverter. For the sake of simplicity, switches are represented as single components on the inverter schemes (*Fig.* 1.), but in reality each one consists of parallel link of up to four MOSFET in TO220 case.

TABLE I
MAXIMUM CURRENT OF POWER SWITCH

$U_{Bat.nom}$ [V]	12						24					
Power [kVA]	0.5		1		2		0.5		1		2	
Topology	PP	2PP	PP	2PP	PP	2PP	PP	2PP	PP	2PP	PP	2PP
$I_{prek.max}$ [A]	50	25	100	50	200	100	25	12.5	50	25	100	50

Such configuration is completely satisfactory in its technical characteristics, price and dimensions [7].

Electrical current values for two input DS voltages, three power ratings and two inverter topologies are provided in *Table* 1. Currents are calculated for minimum input voltage and numbers are rounded. Fields in which current exceeds maximum values (50 A) are marked.

Several popular and available MOSFET types that can be used as components of power switch with acceptable price are listed below. Basic characteristics are provided for each type. 100 V MOSFET are chosen because they can be applied to both operating voltages. [10]

- **IRF540N:** V_{DS}=100 V,
  I_D=33 A/25 °C; 23 A/100 °C,
  I_{Dpulse}=110 A,
  R_{DSon}=44 mΩ/25 °C; 70 mΩ /80 °C,

- **IRF3710:** V_{DS}=100 V,
  I_D=57 A/25 °C; 40 A/100 °C,
  I_{Dpulse}=230 A,
  R_{DSon}=23 mΩ/25 °C; 35 mΩ /80 °C,

- **SPP70N10L:** V_{DS}=100 V,
  I_D=70 A/25 °C; 50 A/100 °C,
  I_{Dpulse}=280 A,
  R_{DSon}=16 mΩ/25 °C; 20 mΩ /80 °C.

In order to achieve full reliability power switches should be over-dimensioned to reasonable extent. That means that components that can endure current pulling caused by transformer magnetization and capacitor charging, giving the values that are several times greater than nominal currents. We can see in the MOSFET characteristics that they can endure impulse currents four times greater than prescribed values. Since every switch has up to 4 MOSFET, fulfilling that condition is very simple.

Over-current protection of the power switches is realized by measuring of output current with transformer (part of power stage) and reduction of output voltages estimated value.

Natural voltage doubling and voltage peaks that cause inevitable parasite components ask for careful choice and calculation of over-voltage protection of PP inverter switch. The first procedure in establishment of the high quality over-voltage protection is the construction procedure and it consists of reducing the extent of parasite components to the lowest possible level and minimization of computational current loops (preventing over-voltage from occurring). With bridge converters this procedure is in most cases sufficient if it is performed in the correct manner, but with PP converters total elimination of over-voltage is not possible on switches if we apply only the construction methods. That means that we have to use some other methods. Use of some of the passive protections (RC, RCD) makes the construction more complicated, it brings in the additional losses and it reduces reliability of the device (larger number of the components), and it also requires complicated calculations with experimental determination of certain parameters. For that reason, in our specific case, active over-voltage protection was used that at the same time protects all the switches in PP with constant voltage follow-up at their drains (ports $D_{h.1}$, $D_{h.2}$), in relation to the power supply voltage (port +*S*) (*Fig*. 1.) [11]. If the voltage between any drain and input voltage is greater than the prescribed one, protection enables both power switches and it released all the accumulated magnetic energy that caused over-voltage. In that manner the protection only follows voltage on the switches and they, through the change in the guidance manner protect themselves. This protection consists of several signal transistors and diodes as well as low power resistors (0.25 W) (*Fig*. 3.), so this is very cheap solution with practically no dissipation and that can be easily placed on the PCB of the inverter power stage next to the power switches that it protects.

It is planned that switching on/off of the power switches is made possible with standard circuit IR2110 [10] (*Fig*. 3.), which controls both PP inverter switches, and it can be conveniently adjusted to over-voltage protection operating and placed on PCB next to the power switches.

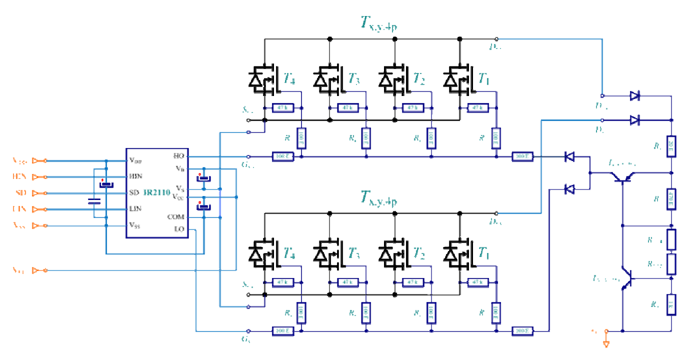


Fig. 3. Triggering of power switches and over-voltage protection.

C. *Cooling of the power stage components*

The simplest assembly solution is the power stage alternative in which all four power switches (with up to four individual MOSFET) are placed on individual, galvanic ally separated heat sinks. Application of PCB for establishment of connections between power components in the power stage lead to the limitation of the space available for the placement of heat sinks. For that reason forced cooling with standard ventilators (12/24 V) was selected, and it includes thermal switches (70-80 °C). Additional reason for the use of forced cooling was also the demand that the heat sink profile should be the simplest possible and with as little mechanical processing as possible, because of lowering the costs of entire device. Ability of the selected MOSFET types to conduct maximum current, and that the power drop remains minimal in them [10] (minimal conduction losses), as well as minimal switch losses (low operating frequency and non-existence of over-voltage in switch turning off) made total losses on switches low, so cheap heat sinks with small dimensions and simple profile could satisfy the demands for adequate cooling.

D. *AVR function*

Important SBN part with which sensitive consumers are supplied through inverter/accumulator battery only when voltage in the mains power system is out of stated boundaries (*off-line*), and which can significantly improve their operating quality is so called AVR function. It is a circuit that fixes voltage in the mains power system and in that manner it expands the scope of input voltages for which the inverter does not have to be switched on (battery use). It is possible to increase and decrease the voltage in one or more steps. AVR principle is demonstrated in *Fig.* 4.

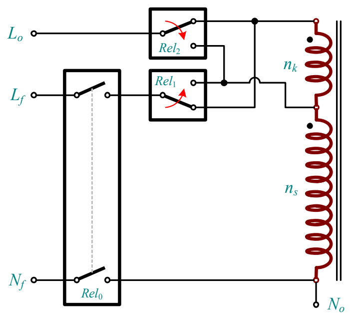


Fig. 4. Basic principle of AVR function (1+1).

Voltage from the mains power system (u_L) is brought between the ports L_f and N_f, and output voltage (u_o) is between L_o and N_o. Transformer consists of the basic (n_s) and correction winding (n_k). Correction of mains power supply is achieved by corresponding switching on/off of relay Rel_1 and Rel_2. Relay Rel_o separates mains system from the rest of device during inverter operating time and it allows realization of power save feature.

- When mains power system voltage is within the boundaries ($u_{L=}$) both relays are switched off and input voltage is equal to output voltage.
- If mains power system voltage is greater ($u_{L>}$), relay Rel_1 is switched off and Rel_2 is switched on. Output voltage is then equal to:

$$u_o = \frac{n_s}{n_s + n_k} u_L = k_{k.sp} \cdot u_L \,, \tag{1}$$

and it is lower than input voltage.
- In case that mains power system voltage is lower ($u_{L<}$), relay Rel_1 is switched on, and Rel_2 is switched off. Output voltage is greater than input voltage:

$$u_o = \frac{n_s + n_k}{n_s} u_L = k_{k.po} \cdot u_L \,. \tag{2}$$

- If mains power system voltage is out of boundaries in which its correction is possible ($u_{L<>}$), relay Rel_o is switching off and the device turns to inverter mode.

Specificity of the presented AVR concept is the use of single correction winding for both increasing and decreasing the voltage, which makes the scope boundaries asymmetrical.

AVR output voltage should be in the following scope:

$$u_o \in [k_{pod} \cdot U_{L.ef.nom} - k_{pre} \cdot U_{L.ef.nom}] \tag{3}$$

- k_{pod}=0.9,
- k_{pre}=1.1,
- $U_{Lef.nom}$=220/230 V.

Maximum voltage increase coefficient:

$$k_{k.po.\max} = \frac{k_{pre}}{k_{pod}} = \frac{1.1}{0.9} = 1.222^{\cdot} \,, \tag{4}$$

is determined in such manner that in case that voltage increase is turned on with u_L=k_{pod}·$U_{L.ef.nom}$ (greatest input voltage in which the voltage increase feature can be turned on) output voltage is not greater than k_{pre}·$U_{L.ef.nom}$. Corrector winding has to have less than or equal number of windings than: (2)(3)

$$n_{k.\max} = \left(\frac{k_{pre}}{k_{pod}} - 1 \right) \cdot n_s = \left(\frac{1.1}{0.9} - 1 \right) \cdot n_s = 0.222^{\cdot} \cdot n_s \,. \tag{5}$$

Minimum and maximum input voltage for which output voltage is satisfactory is: (3)

$$U_{L.MIN} = \frac{k_{pod}^2 \cdot U_{L.ef.nom}}{k_{pre}} = 0.736363 \cdot U_{L.ef.nom} = 169.4_{230} \text{ V} \,, \tag{6}$$

$$U_{L.MAX} = \frac{k_{pre}^2 \cdot U_{L.ef.nom}}{k_{pod}} = 1.3444^{\cdot} \cdot U_{L.ef.nom} = 309.2_{230} \text{ V} \,. \tag{7}$$

It is evident from the analysis that it is possible to make AVR (1+1) (1 increase feature and 1 decrease feature) that in wide range of input voltage change [$U_{L.MIN}$ – $U_{L.MAX}$] provides satisfactory output voltage. (3)

It is not common to operate in such wide range of input voltage in practice, so in regular use there is correction winding in which n_k<$n_{k,\max}$. In that manner creation of transformer is simplified, possible difficulties with output voltage are avoided and the range of tolerable change in input voltage remains sufficiently wide. For the calculation of correction winding we set a condition that in u_L=k_{pod}·$U_{L.ef.nom}$, AVR output voltage is equal to $U_{L.ef.nom}$. From the provided condition we can draw the following:

$$k_{k.po} = \frac{1}{k_{pod}} = \frac{1}{0.9} = 1.111^{\cdot} \,, \tag{8}$$

$$n_k = \left(\frac{1}{k_{pod}} - 1 \right) \cdot n_s = \left(\frac{1}{0.9} - 1 \right) \cdot n_s = 0.111^{\cdot} \cdot n_s \,. \tag{9}$$

$$U_{L.MIN} = k_{pod}^2 \cdot U_{L.ef.nom} = 0.81 \cdot U_{L.ef.nom} = 186.3_{230} \text{ V} \,, \tag{10}$$

$$U_{L.MAX} = \frac{k_{pre} \cdot U_{L.ef.nom}}{k_{pod}} = 1.2222 \cdot U_{L.ef.nom} = 281.1_{230}\ \text{V} \quad (11)$$

If we add another correction winding we can also achieve functions (2+1) (2 levels of increase and 1 decrease) and (2+2) (2 levels increase and 2 decrease). (Case (1+2) (1 level increase, 2 decrease) is not interesting in practice). Larger number of windings and relays means more possibilities for adjustment of input voltage. Because of simplified construction, lowered demand for control electronics and simplification and lowering the cost of the device we have chosen the AVR (1+1) alternative which through single added winding and two relays adjusts changes in input voltage in sufficiently wide range. (6) (7) [11].

E. Power save feature

Efficiency of the device is crucial in case of power supply from accumulator battery, especially if it is charged from renewable source (wind, sun). One of the methods to increase efficiency is so called power save feature. It is the capability of inverter to recognize idle mode or operating under minimal load and in that case it should automatically turn off. Besides that, inverter has to automatically turn on when overload occurs again. Besides significant power save, this feature increases the handling commodity (it is not necessary to turn it on and off, only to hook or remove load). For realization of this feature, besides the relays on the PCB, some adequate circuits are necessary in the control electronics. [11].

F. Electrical schematics

On *Fig.* 5. is provided electrical schematics of entire power part of the inverter which represents maximum variant necessary for achievement of all configurations of the device through the adequate choice of active components.

IV. DESIGN OF PP INVERTER TRANSFORMER

In order to achieve two inverter topologies with two levels of input voltage, three power ratings, with or without AVR, it is theoretically necessary to have 48 different types of transformers. If we use only AVR (1+1) in PP for the practical reasons (there is already one added winding), number of necessary transformer types reduces to 30. When we add the restriction that input current should not be greater than 50 A, which is a consequence of construction design (power stage on PCB), we are left with 16 transformer types which is still a large number for production.

For that reason analysis was conducted and it aimed search for configuration that could make possible the realization of all interest variants of the device through the use of minimal number of different transformer types. Analysis result is provided in *Fig.* 6. It is a transformer with eight windings and with the correct arrangement of the windings it is possible to realize all the variants of the inverter with only two powers: 0.5 kVA (S_{500}) and 1 kVA (S_{1000}). [11]

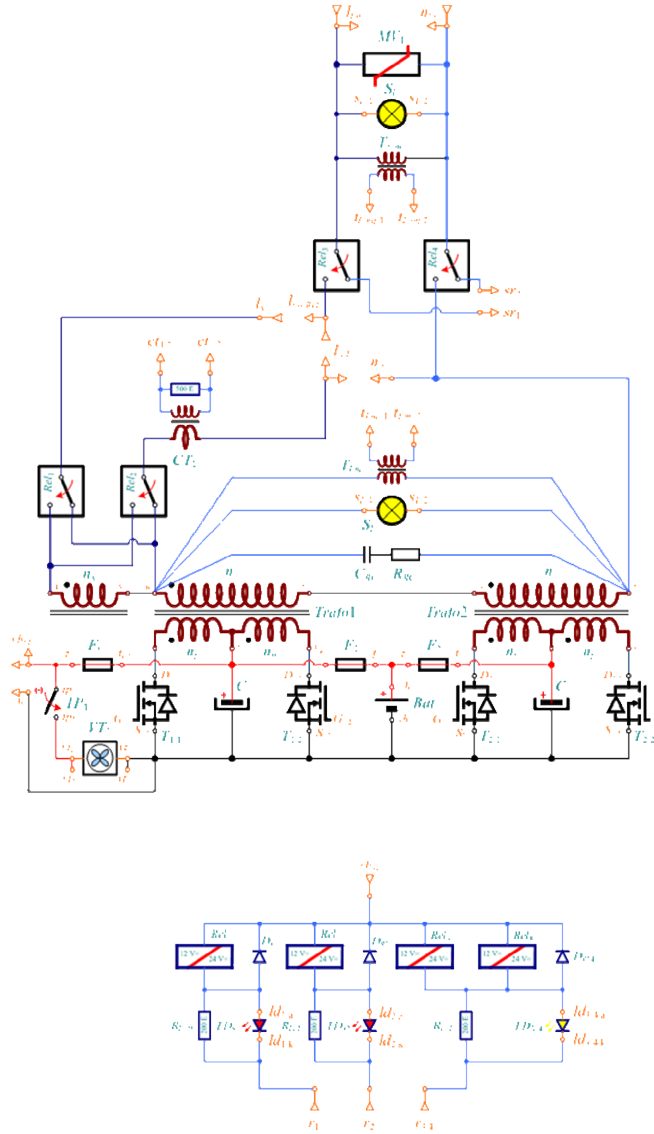


Fig. 5. Electrical schematics of inverter power stage.

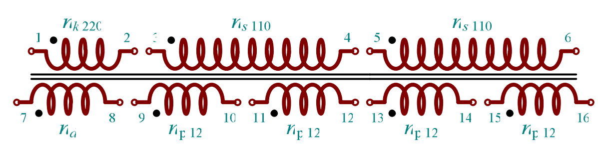


Fig. 6. PP inverter transformer-general case.

- Four primary windings $n_{p.12}$ (ports 9-10, 11-12, 13-14, 15-16) have the number of windings that corresponds to input DC voltage (12V), and wire cross-section area (CSA) that corresponds to current that would, for the given power, run through the windings with input DC voltage 24 V.
- Two secondary windings $n_{s.110}$ (ports 3-4, 5-6) have half of the number of windings that corresponds to the necessary inverter output voltage. Wire CSA for their winding is determined according to current that would run through the windings for provided power and AC voltage 220/230 V (on both windings).
- Added correction winding $n_{k.220}$ (ports 1-2) has to have 11 % of total number of windings (2 $n_{s.110}$) and wire CSA as $n_{s.110}$.

- Additional correction winding, or magnetic energy reset winding n_d (ports 7-8), has to have the same number of windings and wire CSA as $n_{k.220}$.

A. Transformer turn ratio calculation

With regard to PP inverter function, its operating principles and manner of output voltage regulation, as well as type of load (computers, lighting etc.), transformer turn ratio should be chosen in such manner that consumer never experiences voltage higher than maximum allowed ($U_{L.ef.nom}\sqrt{2}\cdot k_{pre}$=$358_{230.1.1}$ V).

$$U_{sek.MAX} = U_{prim.MAX}\,2PO_{I} = U_{L.ef.nom}\sqrt{2}k_{pre} = 358\,\mathrm{V}\,. \qquad (12)$$

Maximum and minimum primary voltages of the transformer are: [11]

$$U_{prim.MAX} = U_{bat.\max} - U_{DS.\min}(I_{\min},\Theta_{\min}) \approx 14/28\ \mathrm{V}\,. \qquad (14)$$

$$U_{prim.MIN} = U_{bat.\min} - U_{DS.\max}(I_{\max},\Theta_{\max}) \approx 10.4/20.8\ \mathrm{V} \quad (15)$$

- U_{DS}, $I_{\min/\max}$: transistor voltage, current,
- $\Theta_{\min/\max}$: operating temperature.

Now the transformer turn ratio is: [11]

$$PO_{I} = \frac{U_{sek.MAX}}{U_{prim.MAX}} = \frac{n_{s.110}}{n_{p.12}} \approx 13\,. \qquad (16)$$

It is necessary to check whether the calculated turn ratio is satisfactory even in cases when mains power system voltage is present in secondary windings. Maximum voltage that occurs in the primary windings always has to be lower than maintenance voltage of accumulator battery, otherwise it would have negative impact on its charging (through diodes of power MOSFET switches), because it is performed by independent charger.

$$U_{prim.MAX}\cdot\sqrt{2} - V_{D} = \frac{U_{sek.MAX}\cdot k_{pre}}{2\cdot PO_{I}} - V_{D} \approx 13/26.8\,\mathrm{V}\,, \quad (17)$$

this condition is also fulfilled.

B. Transformer winding arrangement

Examples of transformer winding arrangements for several configurations and inverter types are provided in *Fig.* 7.

C. Practical realization of transformer

Example of practical realization of type transformer, 1 kVA power, winded according to scheme provided in *Fig.* 6. And with windings according to the provided calculation is shown in *Fig.* 8. it is a compact solution with which is possible to get all the interesting variants of inverters with 1 and 2 kVA powers through simple adjustments.

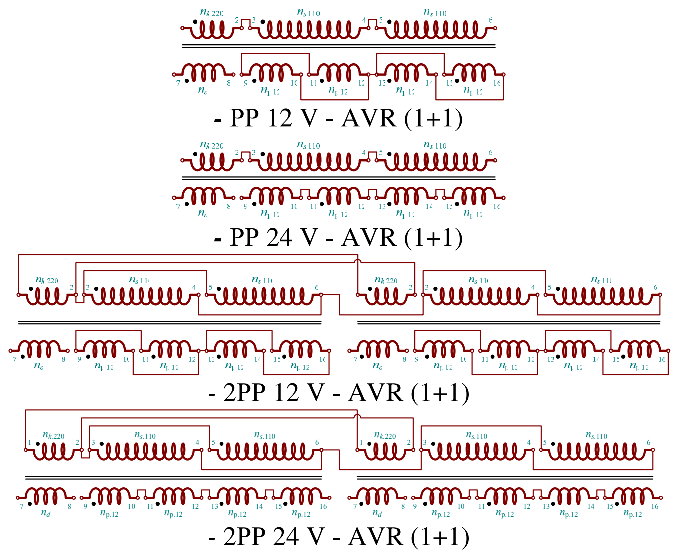


Fig. 7. PP inverter transformer-winding arrangement examples.

Fig. 8. PP Inverter transformer-practical realization.

V. 2PP INVERTER 24 V/ 2 KVA

Example of practical realization of 2PP inverter on PCB is provided in Fig. 9. It is evident that it is simple and cheap construction solution with high integration level and increased reliability. The demonstrated compact module is possible to assemble in vertical or horizontal position, in different cases, and to simply connect it to other inverter components (control electronics module, power transformer(s), battery, etc.)

On *Fig.* 10. is presented 2PP inverter 24 V/ 2 kVA (prototype), realized through the compact power stage on PCB and type transformer 1 kVA, which is part of power supply system from renewable source (solar panel+battery).

Fig. 9. Compact inverter power stage on PCB.

Fig. 10. Compact inverter-prototype.

VI. CONCLUSION

Conducted analysis and presented results show that it is possible to achieve significant improvements of the power stage in PP inverter through the use of PCB. Three power ratings of inverter were realized (0.5, 1 and 2 kVA) depending on input battery voltage (12/24 V) and converter type (PP, 2PP). for greater powers, 3-10 kVA, it is necessary to establish some of the links on copper plates, which increases power capacity of inverter power stage and therefore output power also increases. Further improvements of this class of inverters would be aimed towards integration of control electronics and power stage on PCB in order to gain further compactness, reliability and assembly simplicity of such devices.

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