ELECTRONICS FOR THE COUNTRYSIDE - THE CONCEPT AND REALIZATION POSSIBILITIES OF A HIGH-POWER HIGH-FREQUENCY HIGH-VOLTAGE TWO-WAY ELECTRONIC TRANSFORMER

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Abstract. The possibilities of modern days are to produce electricity in the countryside with solar photovoltaics or wind, but it is problematic for low-voltage networks to withstand the multiplication of loads, especially at low voltage - long wires combination with long distances what are typical for rural places. The article gives a system-level ideas on how to create a solution to this problem in the form of a two-way "electronic transformer" allowing to use the 20 kV power lines, supplementing the idea with an outline of the main technical details of creating critical systems of it, based on our experience in constructing other somewhat similar devices. Performance variants with highlighted disadvantages and advantages are also given.

Keywords: electronic transformer, high voltage, electronics architecture, SMPS

Introduction

The industrial development of the rural places is fundamentally dependent on the possibilities and costs of electrification. Although the majority of farms have an existing electricity connection, it is not everywhere, and now, with the development of solar and wind power plant technologies for individuals or small companies, these grids may be too low-power. One of the things that is disproportionately expensive for a typical farm in rural electrification is high-voltage transformer, but 20 kV transmission lines cannot be connected without it. For example, a substation of over one hundred kW, when buying the cheapest one from China's Alibaba, costs more than 5000 Eur plus transport, customs, VAT, etc. However, when deciding to electrify a homestead located far from existing power lines, especially if it wants to produce electricity, for example, with the help of the sun or wind, or consume it by installing a sawmill or oasthouse, which is a large consumers of current, a transformer of appropriate power, most likely 10-100 kW for 220 V to/from 20 kV is a prerequisite for starting any technologically oriented projects [1]. Our previous work has been to create a 120 kW from 3x380 to 36 kV power supply for the needs of physics experiments processes, which realizes the exact opposite task with SMPS technologies, and we have found that a similar technology could be tried to be adapted to solve the above problem at competitive prices. And there is an idea to make this device bidirectional. The article also discusses the technical details, without which there is no hope of realizing the optimal solution concept. The purpose of the article is to initiate discussion and interest in the implementation of a similar concept project.

Materials and methods

One of the reasons for the mentioned cost is the amount of non-ferrous metals in the transformer and the ferrous metal weight of the core. When raising the frequency to reduce the dimensions of the transformer making it reasonable cheaper, much is determined by the cost of the ferrite. We have found that there exist a low-cost, high-quality ferrite rod manufacturer in India [2] with a general representative in the Czech Republic [3], who offers approximately 1 Eur/piece ferrite square rods with a cross section of 1x1 inch and a length of 4 inches. It allows 0.36 Teslas, up to 50 kHz and a magnetic permeability of 2200, however it is rather fragile and demands a care. The material is also easy to glue with epoxy resin or ciano-acrylate "superglue", may stack together practically any size of core from these rods, E-type, O-type, large, medium, small, starting with a window area of 50x25 or 50x50 or 150 or 200 ... up to metric sizes. Also, the cross section can be 25x25 mm or 25x50, 50x50, 75x75, 100x100 mm, etc. That is, there is no bound limits to the size of the core. Anyway, winding the coils classically, the every second layer end makes a 2x layer voltage against the previous layer begin. If in case of steel-core transformer that rarely is kilovolts, then in case of ferrite core the voltage difference may be dramatic on layer ends but air cannot stand more than 3 kV/mm or 1 kV/mm as more safer value. Therefore our method gives opportunity for 2x smaller safety gaps. Using such ferrites, the price of the transformer drops dramatically if the frequency can be raised to 30-50 kHz or above. However, this is exactly where the problem arises, because the grid frequency cannot be changed. Note, at fig.4 the white wrinkled cable conduit pipes are highly effective method to make the safety distance lesser than in air. This pipe ensures that neighborous wires physically cannot come nearer than 2 heigth of wrinkle and thermoplast have at least 10x higher beat-through voltage in comparizon with air (20 kV/mm to 40 kV/mm for thickness, depending on thermoplast).

True, with the development of semiconductor devices nowadays, in the scientific literature can read about experimental developments of diamond as a semiconductor, which allows to talk about kiloampere currents at megavolt high voltages and megawatts of heat output flows at a normal operating temperature of around 1000 C [4], [5]. However, they are still not available for mass consumption. Something existing for sell are two in one 1200 V igbt in a brick-shaped cube, heat dissipation with running water, current 200-300-500 A, depending on the model [6]. There is a wide selection of such `bricks` for 300 Eur, for 130-150 Eur the offer is already narrower but still existing. Such an element is suitable as a switch transistor when planing a 220/380 V to 20 kV SMPS. Our own experience says that the cheap end products are bit dangerous, as it has poor datasheet facts coverage, and in case of damage, the identical modules already all are sold out and no longer in production. No such problem has been observed with the more expensive markets offer packages. That "brick" transistors are rather sensitive about delta-peak surges, have experience on 500 A mighty igbt connected via the 5 A magnetic fuse just for idle test, where monster-transistor became killed dead but fuse staid undamaged. Proper voltage peaks and current peaks dampfer circuits must be applied everywhere where appropriate and ought be checked by oscilloscope do they are effective enough. For example, the feedline between electrolytes to igbt at on/off shift moment may get the sudden current change, let guess, 400 A 10 ns on 50 cm long wire what is 500 nH inductance, therefore V=L*di/dt=500*400/10E-9=20 Teravolts peak. Practically it may be milder but anyway enough to kill any semiconductor, therefore propper surge MKP capacitors everywhere are essential in proper count, and sandwich lines instead ow simple wire are mandatory as well. We calculated that 120 A case the copper inch wide plane 2 mm plates (strips, busbars) would be proper solution, decreasing the inductance about 4x if distance between both wire-strips is 2 mm and 20x if distance is 0.2 mm. Thus we used about 2 inch wide textollite strip in bandage where both wires are outside, and insulator strip is middle one between them. Result was convincing, only the 30 V voltage spike at sudden amperage jump. At the mounting point of the capacitor bank itself, the most successful design appears to be two appropriately sized square or circular copper or aluminium (or copper) plates separated by a thin insulator spacer. The boards are drilled so that one leg can be soldered or screwed to one board, and the other to the other. Therefore, both plates are drilled for access, but the diameters of the holes are different. Here, too, the resistive parasitic component is suppressed at least 3 times, but the inductive component much more.

We made the cooling system from a 15 mm thick aluminum block, making long holes with a diameter of 6 mm. At the ends, we made transverse holes between the longitudinal channels, and closed the excess holes with a suitable thread. We installed screw-in pipes for water supply. Experience in this field dictates that should definitely try to use a conical thread, or, at the very least, bond the screw with an anti-loosening adhesive, for example, suitable from the Locktite series. Because screw connections are sensitive to dripping, but high voltage has a special relationship with water. For cooling water or ethylene glycol liquid, can use a radiator flushed in the air, because the heat capacity here is not huge, only a few kW, or use a radiator adapted from a suitable vehicle - they can provide a cooling capacity of several tens of kW. Unfortunately, it is not possible to mount the igbt directly on the air cooling radiator, not because of the heat flow itself, but because of the heat flow density (W/cm2). On a smaller scale, we had once successfully solved a similar problem for Peltier cryogenizer platelets using re-evaporation heat pipes from computer equipment, but the heat pipes are not produced in such a large size as required for power igbt assembly. Water is essential (or antifreeze), and in harsh need it may be laid to air cooled radiator afterwards, but straight cooling of transistor with air is nonsense.

It is worth thinking about how to achieve an output frequency of 50 Hz if the transformer uses about 1000 times higher frequency. This is where the pseudo-sine function, well mastered as the high-end Chinese-made 12 V to 220 V inverters, fits in well. There are three methods plus their combinations. a) With the help of a high-frequency SMPS and, accordingly, a ferrite transformer, several supply voltages are made, for example, 155 V, 270 V and 310 V. At the beginning of the low frequency wave of 50 Hz, the first voltage opens, later the second, then the third, and the output product is filtered slightly with a suitable LC filter. b) Produce a single voltage in the same way, but switch on the output transistors by small portions many times with increasing open-state times, starting from very short, feeding the voltage to the output filter so that the time sweep matches the nature of the sin function. In this case, much smaller values of L and C are required for filtering the output signal, and the whole system costs may decline several times cheaper. c) As a subvariant, it is possible to supply the power at equal time intervals, changing the length of the open time, or with an increasing frequency of the on state, but with the same open state time. Or by combining both algorithms, use one at the beginning, but use the other as the peak value of the voltage approaches. Since ready-made chips for this kind of work are not yet produced, the easiest and sure cheapest way to create the right shaping of the control signal is to apply, for example, an Arduino-compatible (Atmega328) chip (in best luck 0.99 USD per piece however the Covid time made a sudden defficiency in semiconductor chips markets), which is rather weak in terms of computational characteristics, but it computing power is completely sufficient for such a task. That is, the control of the signal shape would be dictated by software.

Another significant cost for such a project is the capacitors for the very high voltage high frequency power circuits. Because it develop devastatingly high reactive power, suitable water-cooled high-reactive capacitors command a four- to five-figure cost per piece where 20 000 Eur per capacitor is rather cheap not an expensive offer. We can suggest a more economical solution thoroughly tested in practice [7]. The Rogers company produces several brands of Teflon-based PCB materials for printed circuit boards, despite the long-held dogma that nothing can stick to Teflon surface. The cheapest TC350 has a loss factor (DF) of 0.0015 (compared to 0.015 for common PCB material FR4), the high-temperature material 6035HTC has 0.0013, and the low DF material 5880 has 0.0004. There are also the CuClad 217 and DiClad 880 series which give 0.0009, these two materials have higher breakdown voltage of 45 kV/mm but lower capacitance. This double-sided copper-coated insulator plate is produced in A3 sheet size and priced between 130 and 360 Eur per piece, depending on the brand [8]. At 2...2.2 pF/cm2 one board can deliver up to 2.5 nF per board that withstands 15 kV thinnest and 120 kV thickest. The allowable current density to keep the board significantly below 100 Celsius in self-flow air cooling was measured experimentally, and it was approximately 5 to 10 A per 10 cm2 piece. Respectively, converted to a whole board, it would be able to withstand 6 to 10 kA, although in that case the copper foil of both claddings would have to be thoroughly reinforced. Experiments showed that above 20 A per contact point, the copper begins to delaminate. However, 20 A at 20 kV is also a very huge power.

DC input capacitor batteries may to have an impressive capacity for 100 kW power, tens to hundreds of milifarads, so the connection to the network should be done gradually to avoid transient modes leading to short circuit. For small power, customary are used varistors for this purpose, for slightly larger ones, a resistor with a short-circuit relay over it, or for even more larger power, a magnetic contactor over resistor. However, when currents reach hundreds of A or more, contactors start to cost far too much. We implemented a circuit that creates a three-phase full-bridge rectifier with the help of thyristors. It's strange, but the fact that high-current thyristor `bricks', where there are 2 pieces in each case, costs less than the same current qualified diodes. In addition, it is possible to open each thyristor shortly before the end of the half-cycle of the network, increasing the open time until, reaching from the planned 537 V at least 440 V, when already leave the thyristors on-state in synchronism with an input wave. Circuitry for such a task is simple and highly reliable.

Accordingly, it is not very problematic to make an "electronic transformer" from 220/380 up to 20 kV with a power providing 100 kW or more, thus the solar farm or wind farm may laid the power in the HV mains. It is more tricky to organize the process in the opposite direction transformerless. One of the possible alternatives for DC-DC would be to use the double-pi circuit, as it allows for two-way voltage conversion - both from the network to the consumer and from the consumer to the network. But there are not so much until now DC HV transmission lines in our location, except few experimental. Possible problems in the case of electronics failure, when there is no galvanic isolation between the sides, can be well solved with a ferrite transformer on the low voltage side, because the high voltage cannot be easy split into a high frequency meander pulses due to the lack of sufficiently high voltage switch transistors (however this may be disputed). This may change someday when/if diamond transistor manufacturing will be mastered (what first success was done so eearly as about 2000). However, a simpler approach is to use a one-way devices - one from the ETL to the farm for download and the other from the farm to the ETL for upload, thus using a Step-down converter circuit, Čuk, SEPIC or Zeta circuits or bridge. However, for them, again, a high voltage transistor switches are existing only as a series in avalanche mode (or MMC), so the most tempting for such a purpose would be the capacitive divider converter, where the capacitor made according of our proposed PCB design with a relatively small capacity charges a larger capacitor of lower voltage. It remains to figure out how to discharge this capacitor with as little loss as possible when it is charged from DC high voltage, since operating the divider in AC mode would mean large losses in the lower shoulder. Such technology is described in detail in [9], which is called MMC or modular multilevel converter. Here, the high-voltage capacitor is divided into a series of capacitors, each of which is switched on or off by its own dedicated transistor, on which only a small part of the high voltage falls. Easy-to-use decoupling with optical fiber for transistor Gate control and very simple-to-apply optotransmitters and optoreceivers exists such as pairs of HFBR1528 with 1533 or 2528 with 2523 ought to be mentioned.

One of excellent ways how to ensure a safety in case of malfunctioning the system yet is half-bridge topology, what uses capacitive divider and high frequency ferrite core small sized transformer. But in that case the existance of proper voltage transistor switches is mandatory, and here the Behlke offers [10] a several choices of pre-composed MMC igbt arrays operated like single transistor for voltages 24 kV to 150 kV capable stand up to 400 A in extreme, and speed up to 14 kHz (35 microseconds) - bit slowish but still useable. Exists there at the same factory fast HV thyristors but lesser current working up to 100 ns (or 5 MHz). And exists a MOSFET switch like HTS-300 with 30 kV 20 A and 200 ns fixed pulse length or HTS-330-60 what is just "normal" MOSFET. We believe both may be the well suited candidats for the task, however there are many good other choices at [10]. Yet we have a positive previous experience with Behlke HV switches beforehand, unfortunately, we have not realized this step-down idea until a working prototype because of lack the clientele, so we will not mind if someone else does. The proposed circuit is given in Fig4.

The capacitor bank of the upper shoulder is then charged with direct current, so the question of a multi-kilovolt rectifier is always relevant. Our experience in this field is with 5A 36 kV Graetz bridge, and with 1A 120 kV rectifier. The second one can be implemented very simply (see fig 1) - a suitably long string with 1N4007 at 50 Hz or UC4007 at much higher frequencies, pulling the string into the insulator pipe, which does little to hinder the cooling process, but mechanically strengthens the diodes as a unit. Or contrary, mount everything on the long PCB strip. Whereas diodes in the past were a highly heterogeneous product that required a parallel matrix of shunt resistors to smooth out voltage drops, the modern days diodes are so uniform that no shunt resistors are used and the data sheet does not require them. However, the nomenclature of diodes available for the 5A bridge at 1.2 kV is relatively narrow and stays in TO220 cases. A radiator plate of at least 5x8 cm is mandatory for each case, and even larger is recommended. So we had to assemble around 200 diodes in a series, so a circular insulator material structure with radial grooves was created, where each diode radiator was pushed in a ray-like (radial) direction, squeezed between the two `pancakes'. In the middle of both sides (through the axis of symmetry of the `pancake'), some amount of air was blown inside by means of two computer fans each from own of both sides and it kept the diodes around 80 C at 5A or the heatsink platelets around 60 C. Our experience with assembly - about 5% of the installed diodes revealed a thermal defect in the package when we surveyed under full load with an infrared camera FLIR. At the MIR wavelength, FLIR showed overheating of a few transistors. When performing an audit of the thermal paste smear (repackaging), the defect was gone. Respectively, outgoing control should not be "on the eye", it should be instrumental. And diode screw on the cooler mandatory to have a good Grover washer. Defect in rectifier may be rather detrimental in the HV network line.

Results and discussion

A concept of a powerful device prospectively demanded in agriculture for power conversion is proposed, which in mass production can be cheaper than the existing strategy - to purchase a high-power conventional transformer (substation). Many critical subsystems of such an "electronic transformer" have already been tested within the framework of other projects we have implemented, but it would be necessary to put that experiences together and promote it to interested developers. The Liepāja city high-power transformer production plant exists in Latvia as a branch of a foreign company [11], it distributes the products all over the world. Perhaps it may be interested in conquering this new market niche as well? For the time of now, it seems that the direction from 20 kV to the 220/380 network can be better formed with the help of a capacitive divider (MMC), while the "up" direction can be formed with a ferrite transformer controlled by an ARM processor, which realizes the peidosine function. Also, the on-board processor can well implement the phase synchronization function to the network, which is very important for the safety of electrical networks together with perfect sinwave form creation.

Conclusions

Until now, the entry of SMPS technologies into high-current power has been hindered by factors such as the unavailability of many electronic components in the appropriate current and voltage range. At the moment, the first installations may be found, but it is still possible to implement a new components, like Behlke transistors, Rogers capacitors, Cosmoferrites cores etc. This opens up the opportunity for energy to learn the possibilities of SMPS, and for the development of rural production (except for purely agricultural production), especially in the field of self production of renewable energy without need to transport it by so ineffective low voltage networks. Opening the access to high Voltage lines without having a millions in funding may be a good boost for the economy boom in rural energetics.

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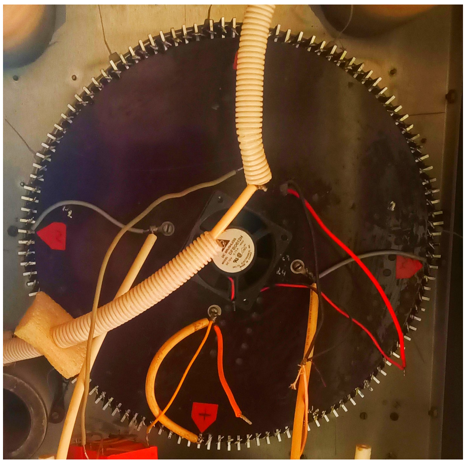

Figure 1: Mechanical composition of 35 kV 5 A rectifier with air cooler. Each rib on the perimeter contains one TO220 diode. Fan blows from center to along the ribs outward.

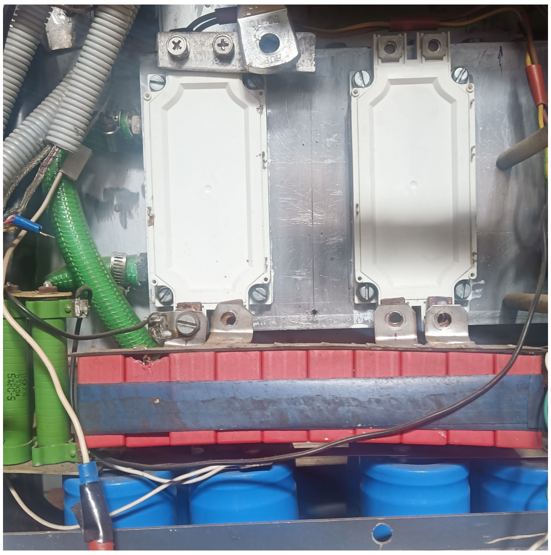

Figure 2: 800 A 1.2 kV igbt H-bridge transistors on water-driven cooler. Red capacitor array below it is voltage anti-spike snubber at moments of on/off processes. Blue electrolytes in bottom are planar sandwich-line connected input DC filter.

Figure 4: Behlke 33 kV 60 A MOSFET switch. Upper wires are HV inputs, lower are optoinsulated controls (Gate).

Figure 3: Ferrite transformer for 120 kW 36 kV on basis of Cosmoferrites core steaks. Each layer of bobbin have shifted ends to 2x decrease the voltage between any neighbour layers.

Figure 5: Cosmoferrite core rods before glue together