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Three-level four-leg flying capacitor converter for renewable energy sources

***Abstract**. This paper presents operation of the four-leg three-level flying capacitor converter interfacing renewable energy source with the grid. Such solution gives possibility to eliminate dy transformer typically used in the three-leg converter based solutions. The four-leg converter with proposed control method enables work in association of electrical grid disturbances (e.g. sags and undervoltages) by switching all legs separately to stand-alone or grid connected mode of operation, what allows for energy transfer between them. In this paper all possible operation modes are discussed and shown. The described control method is modification of well-known voltage oriented control (VOC) based on the proportional resonant controllers. Such control algorithm makes possible to treat each leg of four-leg converter as independent single-phase converter. Simulation study presents good performance and verified validity of the proposed solution.*

***Streszczenie.** Artykuł prezentuje badania symulacyjne trójpoziomowego czterogałęziowego przekształtnika z kondensatorami o zmiennym potencjale sprzęgającego odnawialne źródło energii z siecią elektroenergetyczną. Rozwiązanie takie daje możliwość eliminacji transformatora dy używanego przy najczęściej stosowanym układzie bazującym na przekształtniku trójgałęziowym. Artykuł wykazuje, że przekształtnik czterogałęziowy z proponowaną metodą sterowania pozwala na pracę podczas zaburzeń sieci elektroenergetycznej poprzez indywidualne przełączanie poszczególnych gałęzi do pracy autonomicznej lub sieciowej (**Trójpoziomowy czterogałęziowy przekształtnik z kondensatorami o zmiennym potencjale dla energetyki odnawialnej**).*

Keywords: three-phase four-leg converters, multilevel converters, power electronic interfaces for renewable energy sources.
Słowa kluczowe: trójfazowe przekształtniki czterogałęziowe, przekształtniki wielopoziomowe, sprzęgi energoelektroniczne dla energetyki odnawialnej.

Introduction

When connecting small renewable energy source (RES), e.g. small wind turbine or photovoltaic panel, to four-wire grid the easiest solution is to use single-phase converter. This solution is cheap and simple but has some disadvantages e.g.: only single phase load in stand-alone mode of operation is possible and limit on maximal energy transfer in grid operation mode exists. Therefore in single-phase converter full utilization of produced energy may be not possible what cause the need to store or dissipate energy produced by the RES. These limits makes that the most common solution is to use the three-phase three-leg converter connected to the four-wire grid by *dy* transformer [1], what is shown in Figure 1. The main advantage of such solution, besides of higher energy transfer in grid-connected mode, is possibility to fed asymmetrical load in stand-alone operation mode.

Unfortunately, the mentioned *dy* transformer is quite large and heavy, increases costs double and causes additional losses. This transformer can be eliminated by application of four-leg converter (Fig. 2) [2, 3]. Thus, it gives possibility to fed asymmetrical load in stand-alone mode of operation with precise control of neutral current. Moreover such converter may be treated as three independent single-phase converters. Additional advantages can be achieved when three-level topology is used (e.g. lower voltage on single switch, higher voltage on converter, lower total harmonic distortion, reduction of passive components).

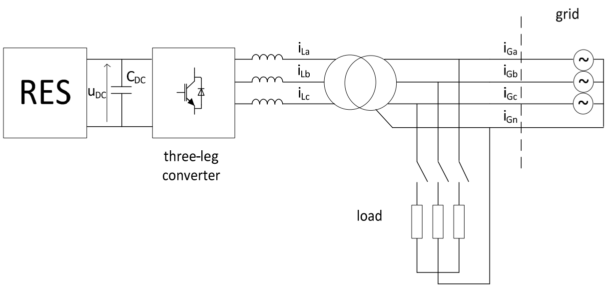


Fig.1. RES connected to the grid by three-phase three-leg converter with *dy* transformer.

There are two basic three-level topologies: Diode Clamped Converter (DCC) [4] and Flying Capacitor Converter (FCC) [5]. The more popular is DCC topology with DC-link divided into series connected capacitors, where midpoint is connected to all legs through clamping diodes. Proper operation of the DCC requires equal voltage on both capacitors, where balancing of these voltages depends on switching states of all legs. Similar to the DCC, for proper operation of the FCC requires that the flying capacitors (FCs) voltages should be equal half of the DC-link voltage U_{DC} [5]. However, contrary to the DCC, balancing of each FC voltage depends only on the switching state of the leg in which given FC is located [6]. Therefore, the FCC topology is more suitable in four-leg applications, where three-phase converter should be treated as three independent single-phase converters. This feature decides about attractiveness of this kind of solution for RES.

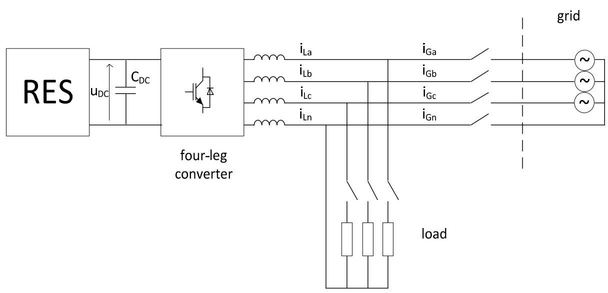


Fig.2. RES connected to the grid by three-phase four-leg converter.

Three-level four-leg flying capacitor converter

The three-level four-leg flying capacitor converter is shown in Figure 3. Each leg consists of four switches: S_{x1}-S_{x4} and FC C_x, where x is the following wire of the grid (a, b, c, n). The switching state of S_{x1} is always negation of the switching state of S_{x4} and the switching state of S_{x2} is always negation of the switching state of S_{x3}. All possible switching states for one leg are shown in Table I. Typically the voltage V_{Cx} is equal $U_{DC}/2$. With this condition the switching state **1** can be divided to two redundant states **1A** and **1B**, which generate the same output voltage $u_{xN}=U_{DC}/2$. As the output voltage does not depend on the type of selected state (**1A** or **1B**), they can be used for independent control of V_{Cx}. Selection between **1A** and **1B** state depends on the V_{Cx} voltage amplitude and the sign of the leg current i_x (Table 1).

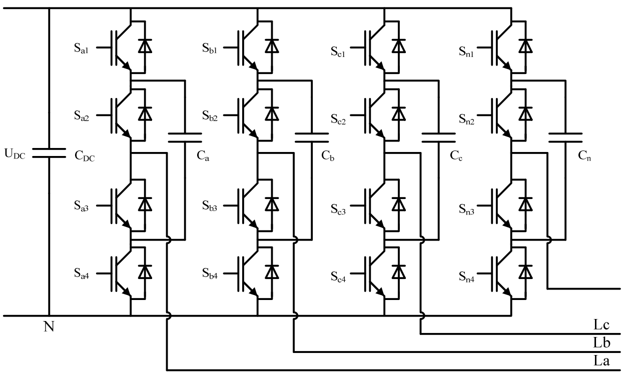


Fig.3. Three-level four-leg flying capacitor converter

Table 1. Switching states for each leg of FCC

State	Switching state				Output voltage level u_{xN}	Capacitor voltage V_{Cx}	
	S_{x1}	S_{x2}	S_{x3}	S_{x4}			
2	1	1	0	0	U_{DC}	constant	
1A	1	0	1	0	$U_{DC}/2$	↑ $(i_x>0)$	↓ $(i_x<0)$
1B	0	1	0	1	$U_{DC}/2$	↓ $(i_x<0)$	↑ $(i_x>0)$
0	0	0	1	1	0	constant	

Modulation techniques

Simplest modulation technique for FCC in analogue implementation is carrier based pulse width modulation (CB-PWM) [7]. From many variants of this technique only phase shifted (PS) [8] modulation is suitable for the FCC, because of natural capability of FC V_{Cx} voltage balancing. In each sampling period every transistor is switched two times (turn on and turn off). Therefore, switching losses are equal for all of them.

Another type of modulation technique for FCC applied in microcontroller is the one-dimensional modulation (1DM), shown in Figure 4 [9, 10] or three-dimensional space vector modulation (3DSVM) [10 - 13]. Both of them need instant value of converter reference voltage in natural coordinates and DC-link voltage (U_{DC}) to choose proper switching state. 1DM and 3DSVM present similar performance (e.g. switching losses, output voltage THD, etc.) but the 1DM permits to treat each leg as independent single-phase converter in contrast to the 3DSVM, based on the three dimensional space vector representation of whole converter. Moreover, the 3DSVM is more complicated in practical implementation. Therefore, the 1DM was chosen as preferred solution for three-level four-leg converters discussed in this paper.

Control method

The most common control method for three-leg converters is well-known voltage oriented control method (VOC) [14]. The classical VOC uses internal current control loops in voltage oriented synchronous rotating reference frame dq. Measured in natural abc coordinates grid voltages and currents are first transformed to stationary $\alpha\beta$ coordinates and next they are converted to rotating dq frame. Grid current in this case is divided into two orthogonal components, where d component determines active power and q component corresponds to reactive power. Because control values in VOC are DC signals a typical PI controller guarantees elimination of current errors in steady states.

Control of four-leg converter is similar but need one more component in all coordinate systems. Thus, there is $abcn$, $\alpha\beta\gamma$, $dq0$ instead of abc, $\alpha\beta$ and dq coordinates (Fig. 5).

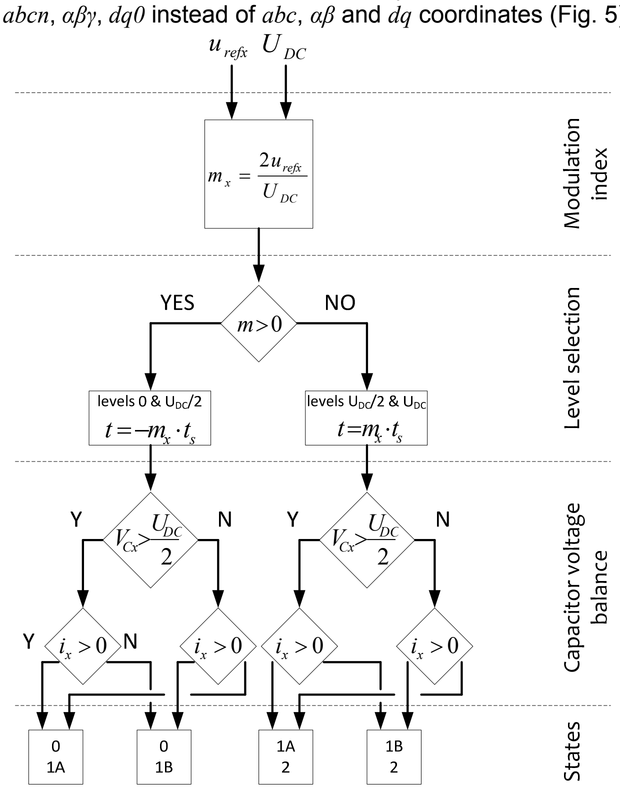


Fig.4. Signal flow diagram of 1DM for three-level flying capacitor converter

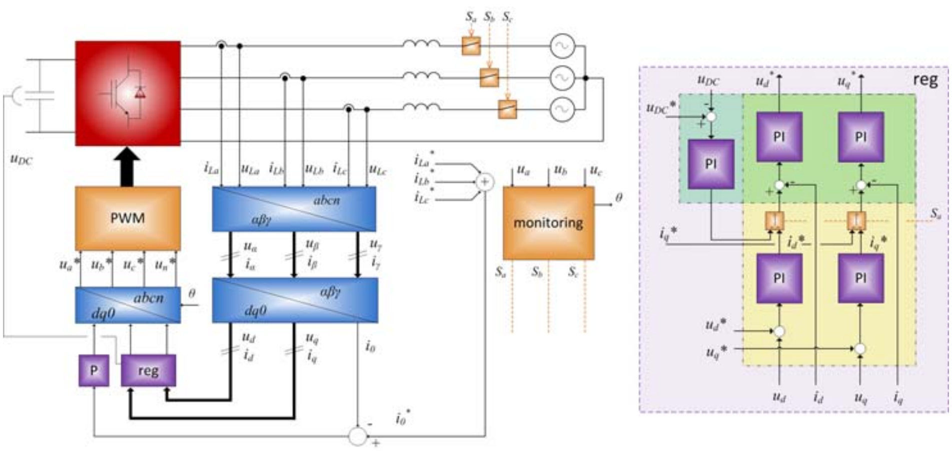


Fig.5. Block scheme of classical voltage oriented control method for four-leg converter with PI controllers

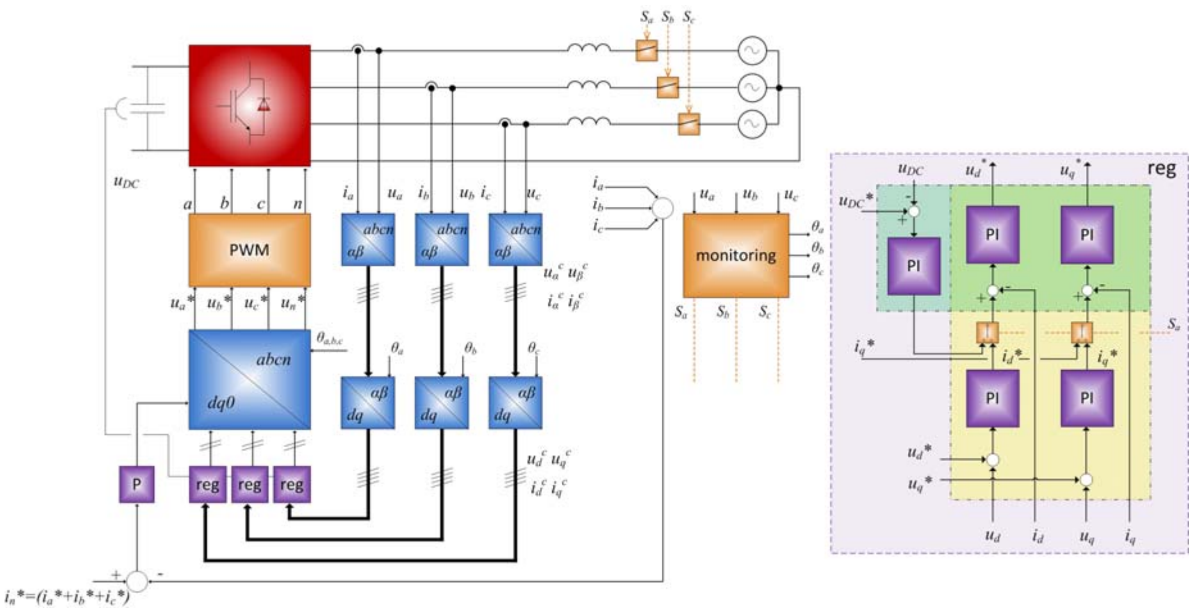


Fig.6. Block scheme of control method with PI controllers

The additional control signal 0 in rotating reference frame is not DC signal, therefore there is a current control loop with only P controller. The serious disadvantage of this solution is difficulties to controlling independently each phase of converter. This drawback can be omitted in modified control method shown in Figure 6, where currents and voltages measured in $abcn$, are virtually transformed to the $\alpha\beta$ and next to the dq coordinates individually for each phase [15]. The grid current of each phase is also divided into two orthogonal components corresponding with active and reactive power of single-phase. Full control scheme is composed of several control loops for each phase:

- internal current control loops in dq coordinate system (green), where two orthogonal components corresponds to active and reactive power,
- external phase voltage loops in stand-alone mode of operation (yellow),
- common outer DC-link control loop (blue).

Control values in dq are DC signals, therefore simple PI controllers may be used. The control in 0 axe stays unchanged as in the previous method. Presented control is able to switch each converter phase to grid-connected or stand-alone mode of operation independently to other converter phases. This gives possibility to transfer energy in both directions at the same time (e.g. two phases are working in grid-connected mode and one phase is working in stand-alone mode or one phase is working in grid-connected mode and two others are working in stand-alone mode supplying only the local load). Main disadvantage of this method is high number of controllers and coordinate transformations.

The number of coordinate transformations can be reduced if control in natural $abcn$ reference frame is used. However in $abcn$ coordinates control values are not DC signals, therefore application of PI controllers is not suitable. However, proportional resonant (P+R) controllers [16 - 18] may be used instead of PI what is shown in Figure 7. The structure of such controller is composed of proportional gain and resonant integrator. The transfer function of P+R controller contains double imaginary pole adjusted to the fundamental grid frequency ω, what allows to track input phase-angle without any error. The control scheme consists only two P+R controllers instead of four PI controllers per phase in stand-alone mode of operation (yellow and green on Fig. 7) as well as instead of two PI controllers per phase there is one P+R controller in grid-connected operation mode (blue).

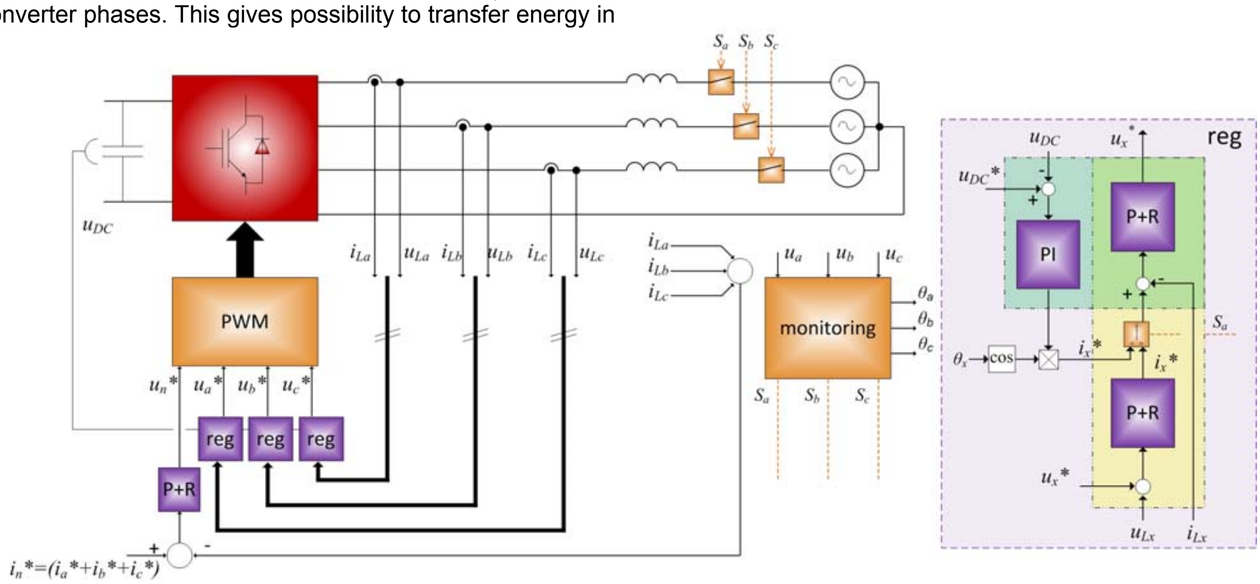


Fig.7. Block scheme of control method with P+R controllers

Table 2. Parameters of simulation model

Parameter			
Parameter		Value	
DC voltage	U_{DC}	700	V
phase rms voltage	U_{Gx}	230	V
Switching frequency	f_s	5	kHz
load	R	20	Ω
Filter inductance	L_f	5	mH
DC capacitor	C_{DC}	1	mF
Flying capacitor	C_x	0,2	mF

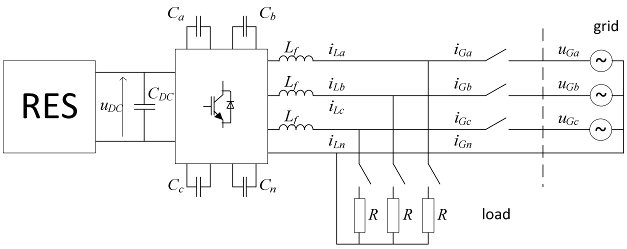


Fig.8. Three-phase four-leg three-level flying capacitor converter

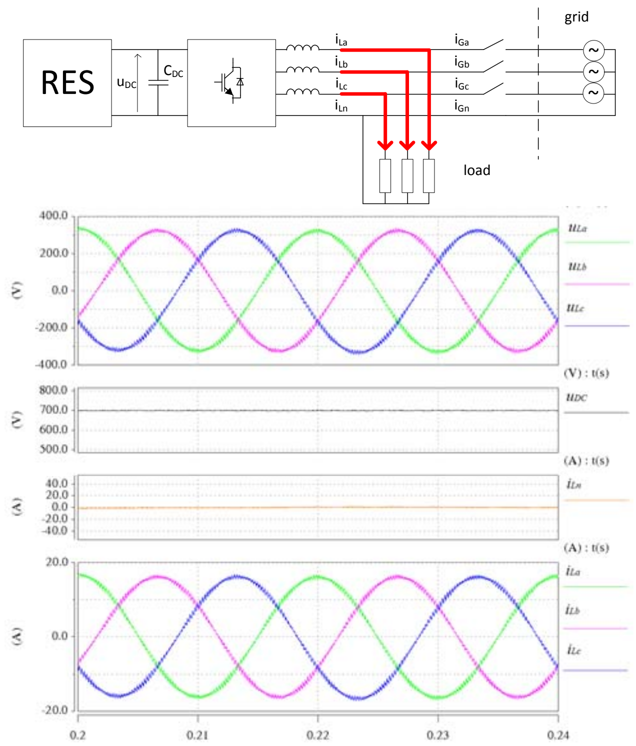


Fig.9 Stand-alone mode of operation. From the top: load voltages u_{La}, u_{Lb}, u_{Lc}, DC-link voltage U_{DC}, neutral current i_{Ln}, load currents i_{La}, i_{Lb}, i_{Lc}

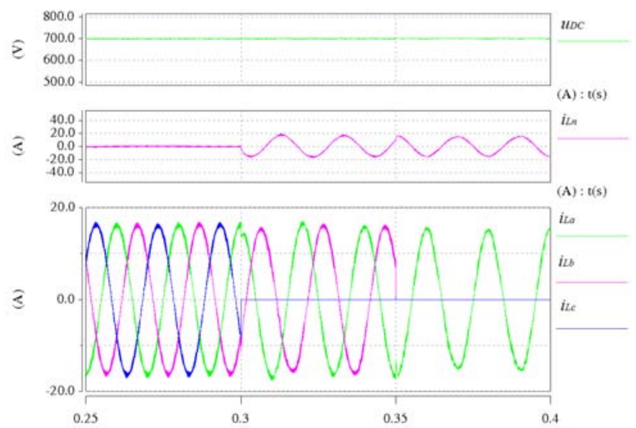


Fig.10. Stand-alone mode of operation. From the top: DC-link voltage U_{DC}, neutral current i_{Ln}, load currents i_{La}, i_{Lb}, i_{Lc}

Commanded DC-link voltage U_{DC}^* is compared with measured value U_{DC} and delivered to PI controller which produces reference current amplitude I_x^*. Reference signal after multiplication by cosinus function of phase angle θ is compared with measured current i_x. Result is delivered to P+R controller, which output goes directly to the modulator. For fourth leg there is also P+R controller instead of P controller.

Results of simulation study

To study the operation of the four-leg three-level FCC the simulation model has been built in the Synopsys Saber Designer software. To simulate the RES, a model of wind turbine with PMSG was used. The grid was modeled as three independent sinusoidal voltage sources u_{Ga}, u_{Gb}, u_{Gc}. Each phase of grid can be connected to or disconnected from the converter by switches S_a, S_b, S_c. The control method and modulation was implemented using the MAST language. Parameters of simulation, according to the simplified model shown in Figure 8, are presented in Table 2.

Simulation studies include the following configurations:

- stand-alone operating mode with symmetrical and asymmetrical load,
- grid-connected operating mode with symmetrical grid voltage,
- mixed mode – grid without one phase voltage, one leg in stand-alone operating mode, two legs in grid-connected operating mode,
- mixed mode – grid without two phase voltages, two legs in stand-alone operating mode, one leg in grid-connected operating mode,
- mixed mode – grid without one phase voltage, without RES, one leg in stand-alone operating mode, two legs in grid-connected operating mode,
- mixed mode – grid without two phase voltages, without RES, two legs in stand-alone operating mode, one leg in grid-connected operating mode.

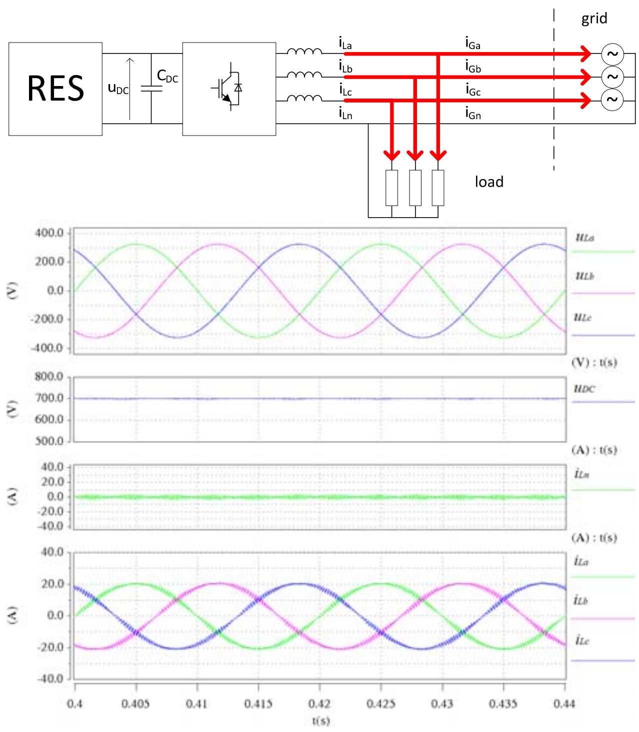
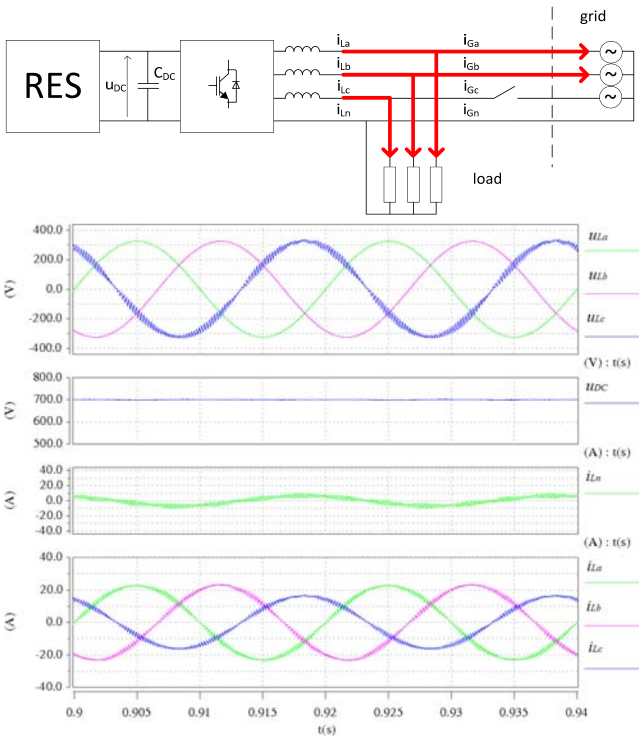


Fig.11. Grid-connected operation mode. From the top: load voltages u_{La}, u_{Lb}, u_{Lc}, DC-link voltage U_{DC}, neutral current i_{Ln}, converter currents i_{La}, i_{Lb}, i_{Lc}



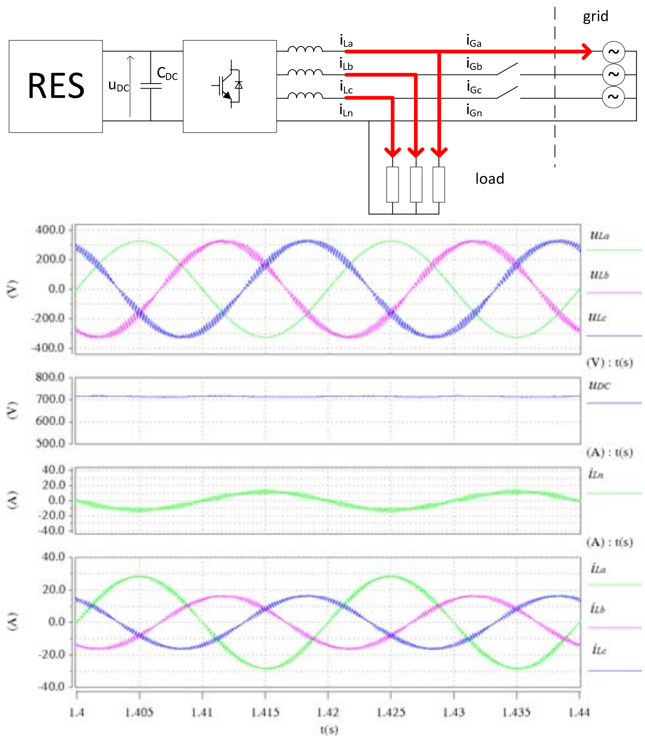
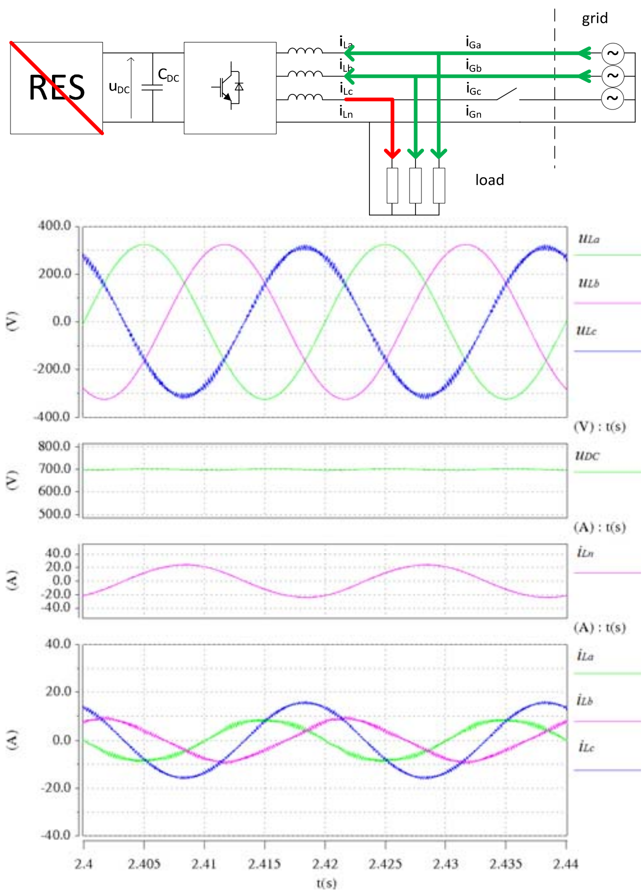


Fig.12. Mixed mode, grid without one phase. From the top: load voltages u_{La}, u_{Lb}, u_{Lc}, DC-link voltage U_{DC}, neutral current i_{Ln}, converter currents i_{La}, i_{Lb}, i_{Lc}

Fig.13. Mixed mode, grid without two phases. From the top: load voltages u_{La}, u_{Lb}, u_{Lc}, DC-link voltage U_{DC}, neutral current i_{Ln}, converter currents i_{La}, i_{Lb}, i_{Lc}



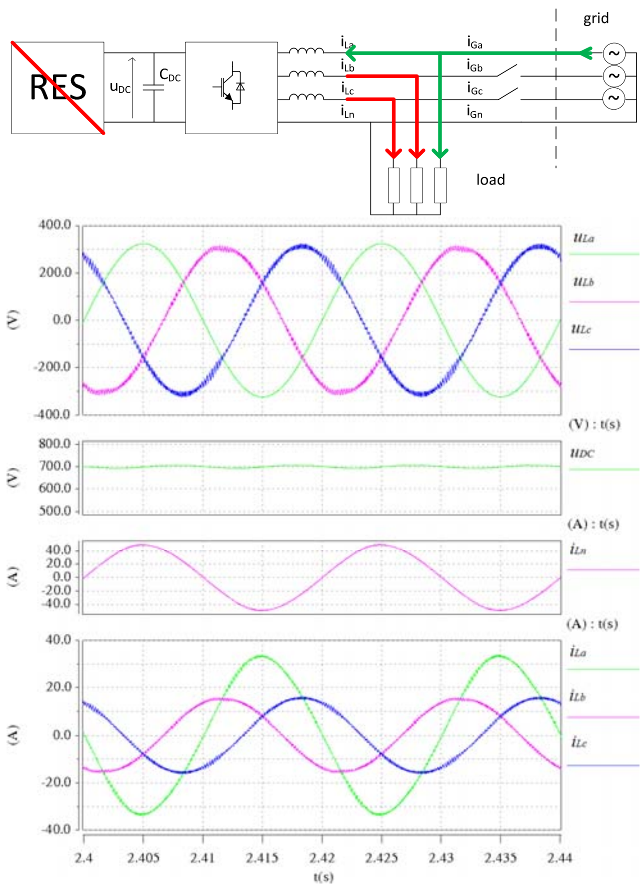


Fig.14. Mixed mode, grid without one phase and without RES. From the top: load voltages u_{La}, u_{Lb}, u_{Lc}, DC-link voltage U_{DC}, neutral current i_{Ln}, converter currents i_{La}, i_{Lb}, i_{Lc}

Fig.15. Mixed mode, grid without two phases and without RES. From the top: load voltages u_{La}, u_{Lb}, u_{Lc}, DC-link voltage U_{DC}, neutral current i_{Ln}, converter currents i_{La}, i_{Lb}, i_{Lc}

Figure 9 presents stand-alone mode of operation with symmetrical local load. Then Figure 10 presents the same mode of operation where:

- from 0,25s to 0,3s three-phase load,
- from 0,3s to 0,35s two phase load,
- from 0,35s to 0,4s single-phase load.

It should be noted that in case of asymmetrical load there is a current in neutral wire i_{Ln}, and if load is symmetrical the neutral current i_{Ln} is equal to zero. Figure 11 presents the grid mode of operation with fully symmetrical grid voltages, where the whole energy is transferred from RES to three-phases of the grid. Mixed modes of operation are shown in Figures 12 and 13, where appears failure of one or two grid phases. In this situation the four-leg converter delivers uninterruptable power supply to three-phase local load, substituting lacking grid phase from RES. Another mixed modes of operation are presented in Figures 14 and 15, where there is lack of some grid voltages but there is no energy or not enough from the RES. The four-leg converter still shows ability to uninterruptable supply three-phase local load, because converter legs still connected to the grid are working in rectifier mode. In this case energy is transferred from legs working in grid-connected mode to other working in stand-alone mode of operation. It is worth to mention that in two last cases current of grid-connected or neutral leg may reach high values, therefore it is necessary to limit current in each leg up to nominal level or oversize the converter. It is especially important for the neutral leg.

Conclusions

The paper presents four-leg converter interfacing renewable energy sources (RES) with the grid. Among important features of the proposed solution are:

- elimination of dy transformer typically used with three-leg converters, what provides higher efficiency and cost reduction,
- possibilities of neutral current regulation.

Moreover, application of the three-level flying capacitor converter (FCC) with voltage oriented control (VOC) in natural coordinates based on proportional-resonant controllers allows to:

- treat the whole system as three independent single-phase converters working separately in stand-alone or grid connected mode of operation,
- reduce current and voltage THD and/or output filter.

The presented simulation results have proven good performance and verified validity of the proposed solution in different modes of operation.

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REFERENCES

[1] Kazmierkowski, M.P.; Jasinski, M.; Wrona, G., DSP-Based Control of Grid-Connected Power Converters Operating Under Grid Distortions, *Industrial Informatics, IEEE Transactions on,* vol. 7, no. 2 (2011), 204-211

[2] Benysek G., Kazmierkowski M.P. Popczyk J., Strzelecki R. , Power electronic systems as a crucial part of Smart Grid infrastructure – a survey, *Bulletin of the Polish Academy of Sciences Technical Sciences,* vol. 59, no. 4 (2011), 455-473

[3] Ali S.M., Kazmierkowski M.P., Current regulation of four-leg PWM-VSI, *in Proc. of, IEEE Ind. Electronics Conf. (IECON),* vol. 3, (1998), 1853-1858

[4] Nabae A., Takahashi I., Akagi H., A new neutral–point–clamped pwm inverter, *Industrial Electronics, IEEE Transactions on*, vol.17, no.5, (1981), 518-523

[5] Meynard T. A., Foch H., Multi–level conversion: high voltage choppers and voltage–source inverters, *in Proc. of IEEE PESC 1992*, (1992), 397-403

[6] Antoniewicz, K.; Jasinski, M.; Stynski, S., Flying Capacitor Converter as a wind turbine interface - modulation and MPPT issues, *Industrial Electronics (ISIE), 2012 IEEE International Symposium on,* (2012), 1985-1990

[7] Rodriguez J., Tutorial on multilevel converters, *in Proc. of International Conf. PELINCEC 2005*, (2005)

[8] McGrath, B.P., Holmes, D.G., Enhanced Voltage Balancing of a Flying Capacitor Multilevel Converter Using Phase Disposition (PD) Modulations, *Industrial Electronics, IEEE Transactions on*, vol.26, no.7, (2011), 1933-1942

[9] Leon J.I., Portillo R., Vazquez S., Padilla J.J., Franquelo L.G., Carrasco J.M., Simple Unified Approach to Develop a Time-Domain Modulation Strategy for Single-Phase Multilevel Converters, *Industrial Electronics, IEEE Transactions on*, vol.55, no.9, (2008), 3239-3248

[10] Leon J.I., Vazquez S., Sanchez J.A., Portillo R., Franquelo L.G., Carrasco J.M., Dominguez E., Conventional Space-Vector Modulation Techniques Versus the Single-Phase Modulator for Multilevel Converters, *Industrial Electronics, IEEE Transactions on*, vol.57, no.7, (2010), 2473-2482

[11] Zhang R., Prasad V.H., Boroyevich D., Lee F.C., Three-dimensional space vector modulation for four-leg voltage-source converters, *Power Electronics, IEEE Transactions on*, vol.17, no.3, (2002), 314-326

[12] Franquelo L.G., Prats M.M., Portillo, R.; Galvan J.I.L., Perales M.A., Carrasco, J.M., Diez E.G., Jimenez J.L.M., Three-dimensional space-vector modulation algorithm for four-leg multilevel converters using abc coordinates, *Industrial Electronics, IEEE Transactions on*, vol.53, no.2, (2006), 458- 466

[13] Stynski S., Space Vector PWM modulator reducing switching losses for three-level flying-capacitor inverters, *Industrial Electronics (ISIE), 2010 IEEE International Symposium on*, (2010), 3912-3917

[14] Wilamowski B.M., Irwin J.D., *Power Electronics and Motor Drives*, *chapter 11: Three-Phase AC–DC Converters*, Taylor and Francis Group, LLC, (2011)

[15] Salaet, J., Pereira, Contributions to the use of rotating frame control and space vector modulation for multilevel diode-clamped single-phase AC-DC power converters, *PhD Thesis*, Universitat Politecnica de Catalunya, Barcelona, Spain, 2006

[16] Teodorescu, R., Blaabjerg, F., Liserre, M., Loh, P.C., Proportional-resonant controllers and filters for grid-connected voltage-source converters, *Electric Power Applications, IEE Proceedings*, vol.154, no.5, (2006), 750-762

[17] Teodorescu, R., Blaabjerg, F., Liserre, M., Loh, P.C., A new breed of proportional–resonant controllers and filters for grid–connected voltage-source converters, *Electric Power Applications, IEE Proceedings*, vol.153, no.5, (2006), 750-762

[18] Blaabjerg, F., Teodorescu, R., Liserre, M., Timbus, A.V., Overview of Control and Grid Synchronization for Distributed Power Generation Systems, *Industrial Electronics, IEEE Transactions on*, vol.53, no.5, (2006), 1398-1409

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