AN IMPROVED DOUBLE FLYING CAPACITOR MULTICELL CONVERTER CONTROLLED BY A PHASE-SHIFTED CARRIER PWM

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***Abstract*—This paper proposes an improved configuration of double flying capacitor multicell (DFCM) converter. The main advantagesof the proposed converter, compared to the conventional lDFCM converter, are the doubling of the number of output voltagelevels and improvement of the output voltage frequency spectrum. This progress is achieved by adding only two low-power switchesand one dc voltage source.However, the number and voltage rating ofhigh-frequency switches and capacitors and the number of highfrequencyswitching's during a full cycle are kept constant. Thedoubling of the number of output voltage levels in the proposedconverter makes it possible to decrease the number of cells, thenumber of flying capacitors, as well as their voltage rating and theamount of stored energy in flying capacitors. Moreover, a modulation method based on phase-shifted carrier pulsewidthmodulationis proposed to control the new converter. Thedoubling of the number of output voltage levels in the proposedconverter makes it possible to decrease the number of cells, then number of flying capacitors, as well as their voltage rating and theamount of stored energy in flying capacitors. Moreover, a modulationmethod based on phase-shifted carrier pulsewidthmodulationis proposed to control the new converter.**

***Index Terms*—Double flying capacitor multicell (DFCM)converter, flying capacitor multicell (FCM) converter**

1.INTRODUCTION

HIGH-POWER industrial applications of converters have been revolutionized in recent decades by the advent of multilevel converters. The logic behind multilevel converters lays in connecting medium-voltage semiconductor switches in series to attain high-power ranges. The most noteworthy advantages of multilevel converters in comparison with their conventional two-level counterparts are synthesizing an output voltage waveform from several steps of voltage with significantly improved harmonic content, reduction of output *dv*/*dt*, electromagnetic interference, filter inductance, etc. These appreciable features have motivated researchers to focus their studies on improvement of topology and control methodology of multilevel converters in recent years. Multilevel converters are categorized, based on their topologies, into three major groups which are diode-clamped converters, cascade multicell converters with multiple isolated dc voltage sources, and flying-capacitor-based multicell converters. The diode-clamped multilevel converter suffers from drawbacks such as imbalance issue of dc-link capacitors voltages and its excessive use of clamping diodes, especially when the number of levels is high, which have constrained its application. Promising alternatives for diode-clamped multilevel converters are multicell structures . Cascade multicell converters, despite their disadvantage of requiring multiple isolated dc voltage sources, are being successfully utilized in high-power applications. However, there are other significant topologies of multicell converters such as flying capacitor multicell (FCM) and its sub topology stacked multicell converters. The FCM converters consist of ladder connection of cells while each cell in FCM is made up of a flying capacitor and a pair of semiconductor switches with a complimentary state. The commutation between adjacent cells with their associated flying capacitors charged to the specific values generates different levels of chopped input voltage at the output side of converter. The voltage balancing of flying capacitors which guarantees the safe operation of the converter is a crucial subject in these topologies. It is well demonstrated via precise mathematical modeling of FCM converters that the capacitors voltage balancing which is called self-balancing occurs if phase-shifted carrier pulse width modulation (PSC-PWM) technique is applied to the converter control pattern. Flying-capacitor-based converters have many attractive properties for medium voltage applications including natural self balancing, transformer less operation, and equal distribution of voltage stress between semiconductor switches. Consequently, many research studies have been dedicated to enhance the topology and control procedure in these promising converters. Besides the previously mentioned advantages of flying capacitor- based converters such as FCM and SM converters,their bulky and costly flying capacitors are the main problems of these converters especially when the number of cells increases. Sadigh*et al.* in proposed a configuration called double flying capacitor multicell (DFCM) converter in which the number of flying capacitors and their voltage rating are reduced significantly. In this paper, the improved configuration of a DFCM converter, called I-DFCM, is proposed to reduce the number of flying capacitors and as a result, decrease the size and cost of the converter in comparison with conventionalDFCM. The remainder of this paper is organized as follows. The advantage of the proposed topology in comparison with the conventional DFCM converter is that the number of output voltage levels is doubled by adding only two low-power switches and one dc voltage source whose voltage rating is a fraction of voltage rating of main dc voltage source[1]-[8]. For proposed single phase I-DFCM converter to validate the effectiveness and advantages of the proposed configuration and its control strategy.To overcome these problemsthe improved configuration of a DFCM converter, is proposed to reduce the number of flying capacitors and as a result, decrease the size and cost of the converter in comparison with conventional DFCM. The advantage of the proposed topology in comparison with the conventional DFCM converter[9]-[28].

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BLOCK DIAGRAM

2. BLOCK DIAGRAM DESCRIPTION

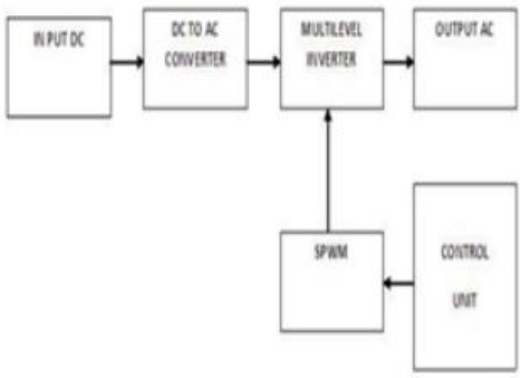

Fig.2.1. Block Diagram

2.1 POWER SUPPLY UNIT:

The dc supply Voltage is given to DC TO AC converter with soft switching cell. The phase-shifted carrier pulse width modulation (PSC-PWM) technique is applied to the inverter control pattern. SPWM is proposed to control the new converter**.**

2.2 PULSE-WIDTH MODULATION (PWM)

PWM or pulse-duration modulation (PDM) is a commonly used technique for controlling power to inertial PULSE-WIDTH MODULATION (PWM) electrical devices, made practical by modern electronic power switches**.**

The average value of voltage (and current) fed to the load is controlled by turning the switch between supplyand load on and off at a fast pace. The longer the switch is on compared to the off periods, the higher the power supplied to the load is.The PWM switching frequency has to be much faster than what would affect the load,which is tosay the device that uses the power. Typically switching have to be done several times a minute in an electric stove, 120 Hz in a lamp dimmer, from few kilohertz (kHz) to tens of kHz for a motor drive and well into the tens or hundreds of kHz in audio amplifiers and computer power supplies.The term *duty cycle* describes the proportion of 'on' time to the regular interval or 'period' of time; a low duty cycle corresponds to low power, because the power is off for most of the time. Duty cycle is expressed in percent, 100%being fully on.The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero. PWM also works well with digital controls, which, because of their on/off nature, can easily set the needed duty cycle**..**

2.3 CONVERTER:

It is used to convert the input DC to AC . Input DC is given to DC TO AC Converter , the converter converts this DC to AC and given to multilevel inverter and it is converted into AC. It regulates the gate pulse.

3 CIRCUIT DIAGRAM

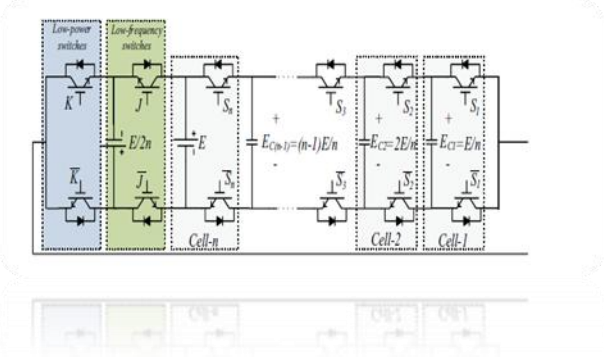

Fig 3.1: Circuit Diagram

3.1CIRCUIT DIAGRAM DESCRIPTION

In Fig. 3.1, is composed of two low-frequency switches,$2n+2$ high-frequency switches, n-commutation cells controlledwith equal duty cycles and phase shift of $2\pi/n$ and $n - 1$ flying capacitors with the same capacitance due to the similar waveform of current in all flying capacitors, and different dcvoltage ratings equal to E/n, $2E/n$, . . ., $(n - 1)E/n$. As a result,the electrical stress on switches is more equally distributedas each high-frequency switch must withstand E/n volts. Theenergy stored in the capacitor i (i.e., U_i) of an n-cell I-DFCMconverter is Furthermore, the output voltage of an n-cell I-DFCM converterhas $4n$+3 levels and its frequency spectrum has the harmonicgroups around the $((2n + 1) \times k \times f_{SW})$ thharmonic where$k$ and $F_{sw}$are the integer number and switching frequency, respectively.

3.2 OPERATING PRINICIPLE:

In this paper, the improved configuration of a DFCM converteris proposed to reduce the number and voltage rating of flying capacitors and as a result, decrease the size and cost of the converter. Fig. 1 shows the proposed 11-level I-DFCM converter which only uses one flying capacitor, while it is required to use nine, eight, and four flying capacitors, respectively, to produce the same number of levels utilizing FCM, SM, and DFCM converters. Moreover, the total voltage rating of flying capacitors and dc-link capacitors to produce the single-phase 11-level output voltage with the peak-to-peak voltage of $10E$ is $55E$, $30E$, and $15E$ in FCM, SM, and DFCM converters, respectively, while it is $7E$ in the proposed configuration of an I-DFCM converter. As shown in Fig. 1,which illustrates the operational principles of an I-DFCM converter, one minor dc voltage source with the voltage rating of $E/4$ (equal to half of the voltage rating of the smallest and the most right flying capacitor) and two complimentary low-power high-frequency switches are added to the most left part of the DFCM converter. The main duty of added minor dc voltage source as well as two switches of$K$is to produce the minor voltage levels, i.e., odd levels, between the major voltage levels, i.e., even levels, produced by DFCM converter. Two added switches of K make it possible that the minor dc voltage source to be connected in series with the major dc voltage source and therefore, produces the small steps and increases the number of output voltage levels. As a result, the minor converter which includes the minor dc voltage source and two low-power switches produces only the minor levels of −1, 0, and +1 in series with the main DFCM converter which produces −4, −2, 0, +2, and +4, i.e., even levels; thus,the proposed I-DFCM converter, as sum of minor and major converters, in total produces 11 levels from −5 to +5 in one unit steps.

3.3 PRODECURE:

The switching procedure of an 11-level two-cell I-DFCM converter is as follows. As shown in Fig. 1, $V_{ref,abs}$, which is the absolute value of output reference voltageV_{ref}, is intersected and compared with five phase-shifted carriers. As seen, the output of comparator #Y is 1 when the $V_{ref,abs}$is higher than the carrier #Y and is 0 when the $V_{ref,abs}$ is lower than the carrier #Y. Then, the output of comparators are added together to generate the output reference voltage in a staircase waveform$V_{ref,abs,s}$. The notation of abs and s refer to absolute value and staircase waveform, respectively. Afterward, the modified output reference voltage (called$V_{ref\text{-}mdf}$) can be generated as follows:

$$V_{ref,mdf}=V_{ref,abs,s}*sgn(V_{ref})+(1-sgn(V_{ref}))/2*5 \quad (1)$$

Wheresgn(x)is the signum function and equals +1 when the signal x is positive and equals −1 when the signal x is negative.

According to the modified output reference voltage Vref-mdf, the reference of a DFCM converter Vref-DFCM is calculated to produce the major levels of 0, +2, and +4, i.e., even levels. In other words, Vref-DFCM can be expressed as

$$V_{ref\text{-}DFCM}= 2 \cdot ((V_{ref\text{-}mdf})/ 2) \quad (2)$$

After this calculation, the reference of a DFCM converter $V_{ref\text{-}DFCM}$ is intersected with two phase-shifted carriersto determine the states of DFCM converter's switches, i.e., J, $S2$, and $S1$. In the next step, as shown in Fig. 1, $V_{ref\text{-}DFCM}$ is subtracted from $V_{ref\text{-}mdf}$to calculate the status of switch K. If the result of subtraction is 1, the switch K is ON and if the result of subtraction is 0, the switch K is OFF. It should be noted that switches $K$are complimentary. To make the operational principle of an I-DFCM converter much more comprehensible, the switching states of a two-cell-11-level I-DFCM converter are illustrated in Table 3.1. The switch X is ON when its state is 1 and is OFF when its state is 0. Moreover, Fig. 3.1 shows the general configuration of an n-cell $4n$+3-level I-DFCM converter whose control method is as follows. First, the $V_{ref,abs}$waveform, absolute value of output reference voltage, is intersected and compared with $2n$+1 phase-shifted carriers. According to the modified output reference voltage $V_{ref\text{-}mdf}$, the reference of a DFCM converter $V_{ref\text{-}DFCM}$ is calculated by (2), and then the waveform of $V_{ref\text{-}DFCM}$ is intersected with n phase-shifted carriers to determine the states of n-cell DFCM converter's switches. In the next step, the state of complimentary switches $K$is determined according to the previously explained procedure.

3.4 COMPARISON OF I-DFCM WITH OTHER CONVERTER:

The comparison between the different types of flying capacitor-based multicell converters, i.e., FCM, SM, DFCM,and the proposed I-DFCM converters, for producing the identicaloutput voltage with equal number of levels ($4n$ + 3 levels)and equal peak-to-peak output voltage ($2E$).

The amount of stored energy in all dc-link and flying capacitors and shows total voltage rating of all dc-link and flying capacitorsin FCM, SM, DFCM, and I-DFCM converters. According To , the stored energy in, as well as the total voltage rating of,all dc-link and flying capacitors to produce $4n$+3-level output voltage with $2E$ peak-to-peak value in FCM, SM, DFCM, andI-DFCM can be calculated.

3.5 COST AND SIZE COMPARISON OF DFCM AND I-DFCM

It is obvious that the size and cost of the DFCM converter is much lower than the size and cost of the FCM converter in producing the identical output voltage with the same condition and power rating. The reason is that the number of switches (with the same specification and power rating), the number of flying capacitors, and the number of dc voltage sources in the DFCM converter are half the number of those components in the FCM converter. Therefore, the price of the DFCM converter is much less than the FCM converter in the same power rating. Thus, the proof of reduction of size and cost of I-DFCM converter in comparison with DFCM converter means that the size and cost of the I-DFCM converter is the lowest among the three mentioned converters. A comparison between the main parts, i.e., switches, gate drivers, gate drivers' isolated power supply, and flying capacitor of the DFCM and proposed I-DFCM converters is illustrated next. The information about size and cost of the mentioned components are obtained from an online distributer such as NEWARK, DIGIKEY, and MOUSER, or the website of some companies such as IRF and ABB. In this part, any increase or decrease in the I-DFCM converter's size, cost, and components count is compared with the DFCM converter. Also, it is assumed that these converters have the same specifications and operational conditions such as the same load impedance, maximum output voltage, number of voltage levels, output current, and switching frequency.

3.5.1. Size and Cost Comparison of Required DC Links

DFCM and I-DFCM converters need one and two dc-link voltage, respectively. However, the current rating of those dc links is almost the same in both converters, due to the same load current, and the voltage rating of one dc link in DFCM is equal to the total voltage rating of two dc links in I-DFCM. If the combination of transformer, diode rectifier, and dc capacitor is used to make the dc link, it is possible to implement. In these configurations, fromthe transformer point of view, the number of primary winding'sturns, total number of secondary winding's turns, wire thicknesin primary and secondary side, total power rating, and core size are the same as shown in Fig. 3.2(a) and (b). The only difference between Fig. 3.2 (a) and (b), from the transformer point of view,is that Fig. 3.2 (b) needs isolation between two windings at thesecondary side. The price of this isolation is not significant incomparison with the price of the whole transformer; as a result, the price of the transformer in Fig. 3.2 (a) and (b) is almost same. Moreover, the total price of diode rectifier and dc capacitor to make the dc link with voltage rating of n p.u. is approximately the same as the total price of two diode rectifiers and two dc capacitors to make two dc links with voltage ratings of $(n-1)$p.u. and 1p.u. As a result, it can be concluded that the total priceto make the required dc links in I-DFCM and DFCM is nearlythe same.

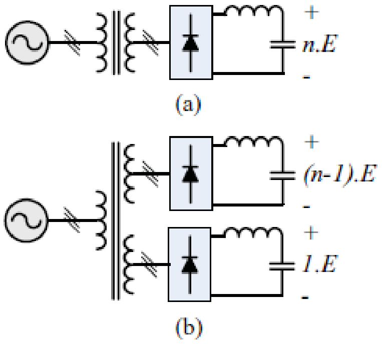

Fig. 3.2. Configuration to make required dc links in (a) DFCM converter and(b) proposed I-DFCM converter.

3.5.2 Size and Cost Comparison of Switches

According to Table II, the number of high-frequency switches in the proposed I-DFCM converter is almost half the number of high-frequency switches in the DFCM converter to produce the same number of levels. However, the voltage rating of switches in the I-DFCM converter is two times higher than the voltage rating of switches in the DFCM converter to produce the identical output voltage; but the current rating of switches in both converters is the same because it was assumed that the output voltage and current is the same in both converters. The price of switches with 2 p.u. voltage rating and 1 p.u. current rating is around 150–200% of the price of switches with 1 p.u. voltage rating and 1 p.u. current rating (The price of switches with voltage rating up to 1200Vwas only available in the aforementioned online distributor or companies). This means that the price of all high-frequency switches in the I-DFCM converter is almost 75% or 100% in the worst case, compared with the DFCM converter. It should be mentioned that the voltage rating unit is different from the current rating unit. In the comparison process, an attempt was made to compare the switches with each other to have almost the same condition such as power dissipation, power loss, total gate charge, and turn-on time. On the other hand, producing the identical output voltage by DFCM and the proposed I-

DFCM needs the same high-power low-frequency switches. Thus, it can be pointed out that the ratio of total price of all switches in the I-DFCM converter to the DFCM converter is 1 for the worst case and 0.75 for the best case.

3.5.3. Size and Cost Comparison of Gate Drivers

The price of gate drivers for switches with voltage rating of 2p.u. is about 100–140% of the price of gate drivers for switches with a voltage rating of 1 p.u. It should be mentioned that the comparison was done between ICs with the same specification such as output current and type of package. Due to the reduction of the number of switches in the I-DFCM converter by 50%, the required number of gate drivers is reduced by 50% in the IDFCMconverter; this issue causes a reduction in the price of all required gate drivers by 50–70%. Moreover, the size of allrequired gate drivers can then decrease by 50%.

3.5.4. Size and Cost Comparison of IsolatedPower Supplies

Each gate driver needs one isolated power supply to be able to operate while the price and especially the size of the isolated power supply are comparable with the price and size of the gate driver. Due to the reduction of the number of required gate drivers by 50% in the I-DFCM, the number of required isolated power supply is decreased by 50% which results in a significant decrease in the size and cost of all required isolated power supply.

3.5.5. Size and Cost Comparison of Flying Capacitors

Flying capacitors are remarkable components from the costand size point of view in flying-capacitor-based converters. Furthermore, in flying-capacitor-based converters, the price of the dc flying capacitors is much higher (sometimes ten times higher) than the price of switches.Although, due to the identical output current, the capacitanceof flying capacitors is the same in both the I-DFCM and DFCM converters, the number of flying capacitors in the I-DFCM is decreased by more than 50%. For example, a three-cell 15-level I-DFCM converter with maximum voltage of 15 p.u. needs two capacitors with voltage rating of 2 and 4 p.u., while the DFCMconverter needs six capacitors with a voltage rating of 1, 2, 3, 4, 5, and 6 p.u. to produce the same output voltage. In general,the I-DFCM converter needs $n - 1$ flying capacitors to produce$4n + 3$-level output voltage while the DFCM converter needs$2n$ flying capacitors. Even if we assume that the capacitors with different voltage rating have the same price and size, which is not the case, the size and price of the required flying capacitors can be reduced by more than 50%. In practice, it can decrease much more than 50%. Moreover, capacitors have less life time in comparison with other components. As a result, decreasingthe number of capacitors makes these converters more reliable. Moreover, reduction in the size and number of required components causes a decrease in the size of the PCB. In conclusion, the price and size of the proposed I-DFCM converter are significantlyless than the price and size of the DFCM converter for the same operational condition and specification.

4. SIMULATION RESULTS

4.1 GROUPING EXISTING BLOCKS INTO A SUBSYSTEM

If a model already contains the blocks needed for a desired subsystem, you can create the subsystem by grouping those blocks:

Enclose the blocks and connecting lines that you want to include in the subsystem within a bounding box. For example, the figure below shows a model that does signal processing. The Abs, Sine Wave Function and Add blocks that do the signal conversions are selected within a bounding box. The box illustrated can be selected by clicking the mouse at the upper left position, and then while depressing the right mouse button drag to the lower right position.

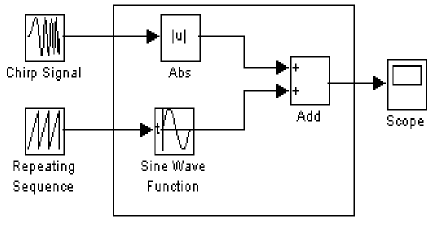

Fig 4.1.Simulink subsystem

The components within the box will be selected when the mouse button is released.

Choose Create Subsystem from the Edit menu. Simulink replaces the selected blocks with a Subsystem block. The figure below shows the model after the Create Subsystemcommand has been chosen. If necessary, the Subsystem block can be resized so that the port labels are readable.

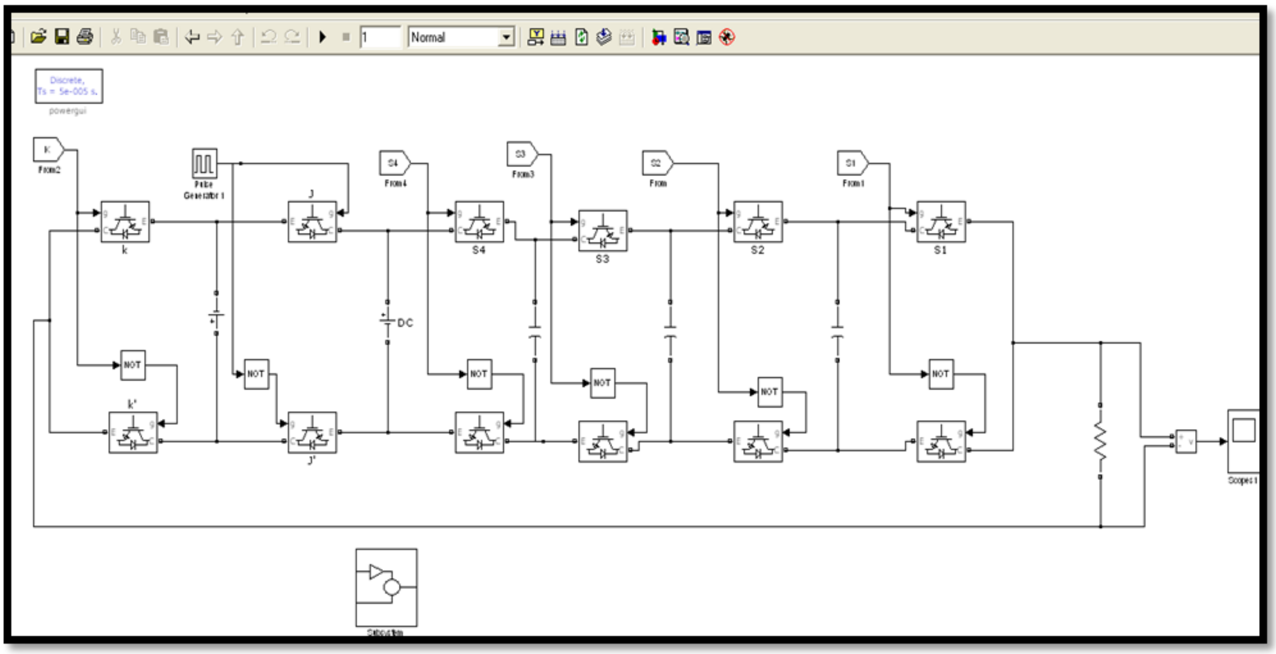

Fig. 4.2 Circuit Diagram

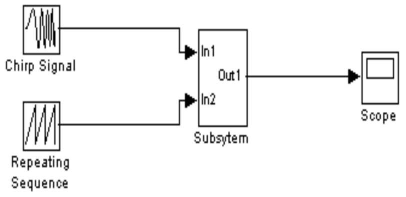

Fig 4.3.Model after create subsytem

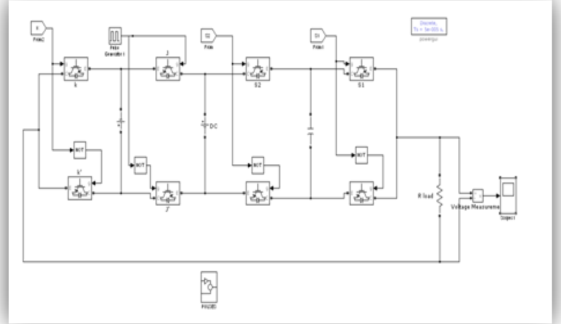

Fig 4.4 Simulation circuit of Flying Capacitors reduction in 11 level two-cell converter

4.2 RESULTANT WAVEFORMS

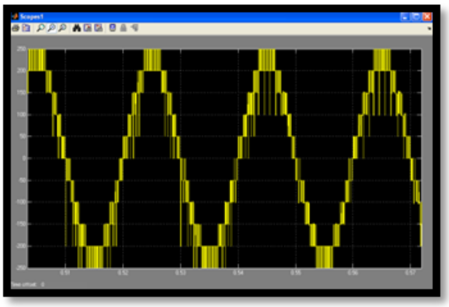

Fig 4.5 Simulation circuit of Flying Capacitorsreduction in 19 level four-cell converter

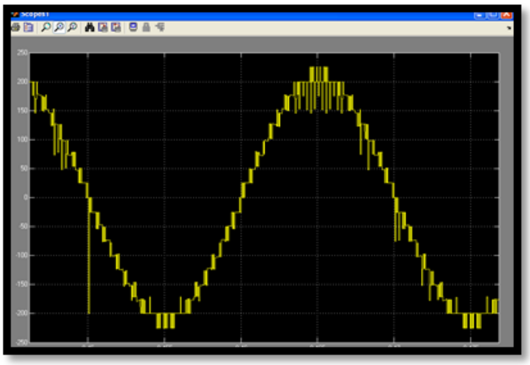

Fig 4.6 Output waveform of 19 level four-cell I-DFCM converter

5 CONCLUSION

Even though the flying-capacitor-based converters such as FCM, SM, and DFCM offer remarkable advantages for medium voltage and high-power applications, they unfortunately require bulky and costly flying capacitors. This paper proposes a new configuration called the I-DFCM converter to decrease the number of cells and flying capacitors as well as the flying capacitors' voltage ratings. This results in a reduction of the cost and size of the flying-capacitor-based converters and makes them more practical. These achievements are obtained by adding onecell, including one dc voltage source whose voltage rating is a small fraction ofthe main dc-link voltage rating,and two low-power high-frequency switches, to the conventional DFCM converter. The added cell produces the minor levels (odd levels) between the major levels (even levels) while the voltage rating and total power rating of the switches are almost the same in both the proposed and the conventional converters. Moreover, a proposed modulation method is implemented to control the new I-DFCM converter while the natural self-balancing property still exists to balance the voltage of flying capacitors in their desired level without any active or feedback control. In addition, the complete comparison between the conventional flying-capacitor-based converters and the proposed one is illustrated regarding the number of devices, voltage rating of devices, and the amount of stored energy in the converters. Moreover, the simulation results of the proposed I-DFCM, FCM, and DFCM converters producing 11-level output voltage are illustrated and compared with each other. The provided simulation results together with the measured experimental results verify the good performance and feasibility of the proposed converter.

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