Design of Cascaded H-bridge Multi-level Covnerter for Power Coolant Pump

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***Abstract*— This paper discussed the analysis and simulation of cascaded H-bridge (CHB) multi-level converter for power coolant pump with demand on high reliability. Multi-level inverters are designed to control medium-voltage motors, energy conversion, active power filtering, and many other applications. Compared to two-level converters, they achieve less voltage distortion (smoother and less distorted AC output voltage) and higher reliability. First, the function of the CHB converter and the most suitable control method is described in detail. In the last part, the 13-level converter is simulated in the normal operation state and the fault operation state. In the operation under normal conditions, phase voltage, line-to-line voltages, and degree of voltage distortion are displayed. In the operation under fault condition, where some of the converter cells are bypassed, line-to-line voltages and torque are displayed.**

Keywords—Cascaded H-bridge (CHB) converters, power coolant pump, PS-PWM method, fault operation, simulation

I. INTRODUCTION

A technology enabling massive development of medium-voltage high-power applications is based on multilevel converters, which have a wide range of usage [1]-[3]. In transport, multi-level converters are used as traction drives for trains, electric cars, and ship propulsion [4]-[5]. An interesting field of application is also the energy conversion and treatment including interfacing units between grid and renewable energy from solar or wind plants, reactive power compensation, and active power filtering [6]-[10]. Another application may be the power interface between two grids with other frequencies, such as powering a 16.7 Hz single-phase grid (for railway) by a 50 Hz three-phase grid [11]. The last applications can be found in the petrochemical industry (compressors and pumps), the mining industry (conveyors for ore transportation), the cement industry (power fans) and the metal industry (rolling mills) [4], [12]-[13].

Multi-level converter technology provides more than two voltage levels of output voltage, which means it is a sum of voltage levels with less distortion, less switching frequency, and higher efficiency. The most widespread topology of the power converter is neutral point clamped (NPC) most often in the form with three-level output. This topology reduces the number of power devices and volume of the converter, but the main drawbacks are more complicated control (especially at five and more levels inverters) and reduced reliability. A very similar topology is a flying capacitor (FC) converter. The major difference is that a flying capacitor is used instead of a clamping diode. The advantage of this topology is the possibility to increase the number of voltage levels, which causes greater stability and redundancy. Perhaps the main drawback is the large and expensive flying capacitors. Other topology of multilevel converters represents cascade H-bridges converters with a serious connection of H-bridges. They are characterized by great reliability and redundancy, but with increasing volume and cost of the converter. Moreover, each H-bridge requires its own insulated DC source [1], [14]-[15]. Modification of CHB topology is modular multilevel converters (M2C) [16]. This is a very similar concept to that of CHB but with the difference that H-bridges are replaced by half-bridge with a capacitor.

This paper investigates the conception of multilevel medium-voltage converter for power coolant pump with demand on high reliability. Failure could cause serious material damage or death. The main attention is dedicated to the analysis of the CHB converter which is the most suitable variant for this application. Some characteristics of CHB converter were simulated for motor in open-loop control such as line-to-line voltages, phase voltage and spectrum of harmonics. The last part is devoted to the simulation converter under fault condition, where all line-to-line voltages, torque, and more are shown.

II. REVIEW OF CHB CONVERTERS

Series connection of two or more one phase H-bridges provides CHB multilevel converter. Example of one phase CHB converter is illustrated in Fig. 1. Single H-bridge can reach three different voltage levels and four possible switching states. For example, in the H-bridge *A*, the positive output voltage of DC link is achieved by switch on S_{A1} and S_{A4}, the negative output voltage is achieved by switch on S_{A1} and S_{A4} and the last one, zero voltage can be generated by switch on S_{A1} and S_{A2} or S_{A3} and S_{A4}. To avoid DC-link short-circuit it is forbidden to switch on two semiconductors above at the same time. The inverter H-bridges are connected in series and that will make possible to generate different levels of output voltage when total inverter voltage output is increasing. Count of output voltage levels CHB inverters with k H-bridges is $2k+1$.

Each single H-bridge has four possible switching states, where two of them have redundant output. In the case series connection of two H-bridges, sixteen possible switching states arise and the number of redundancies increases.

The main advantage of this topology of the multilevel converter is its high degree of redundancy. As already discussed when the number of H-bridges grows, the redundancy rate is also increasing (enable fault-tolerant operation). Another advantage is the fact that the total output voltage of the converter can be many times greater than the blocking voltage on the semiconductors. Hence, semiconductors have to block only the voltage of the insulated DC source, not the total DC-link voltage of the converter. A major drawback is the need for each H-bridge to provide its own insulated voltage source. A transformer with several secondary windings (according to the number of H-bridges) is most often used.

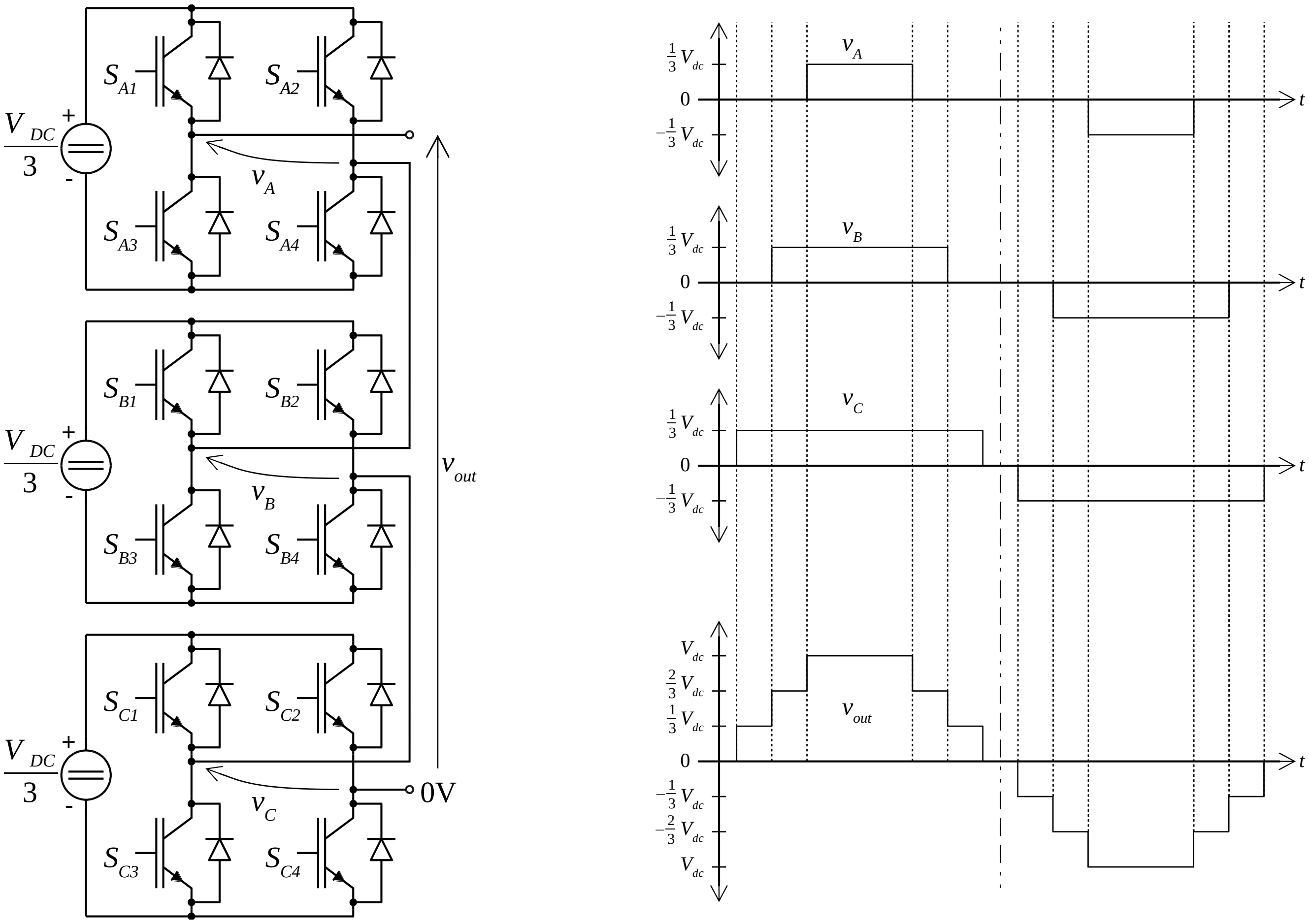

Fig. 1: Seven-level cascaded H-bridge converter: a) power circuit and b) single phase output.

Each secondary winding requires its own rectifier since the volume and cost of the converter increases.
In this application reliability is the main aspect therefore this high-voltage converter topology appears to be the most appropriate.

III. Phase-shifted PWM modulation method

The most optimal method for control CHB inverters is phase-shifted PWM (PS-PWM) techniques. Other control methods for CHB converters are described in [17]. One cell of CHB converter represents a three-level converter that can be controlled by traditional bipolar and unipolar PWM techniques. Each cell of CHB converter can be modulated independently of the others, but using the same carrier triangle signal for all cells. A phase shift is applied to triangle carrier signal for each cell. For better understanding, the implementation diagram of the PS-PWM method for the seven-level CHB is illustrated in Fig. 2. It has been shown that the lowest distortion of the output voltage is achieved by having a phase shift of 180° or 360° / *x*, where *x* is the number of cells in the converter. In this way, the output voltage will have a stepped waveform with corresponding voltage levels. An example principle of generation output voltage for seven-level CHB is shown in Fig. 3. Note that all voltages are in per units.
The power is equally distributed over each cell because the cells are controlled by the same control signal and a carrier triangle signal at the same frequency, which is a great advantage. Another advantage is a fact, that phase shift of triangle carrier signal for each cell cause *x* times higher frequencies of PWM than the carrier triangle signal alone. This is the reason, why it is possible to achieve low THD and low switching losses of switch device with relatively small frequencies of carrier triangle signal.

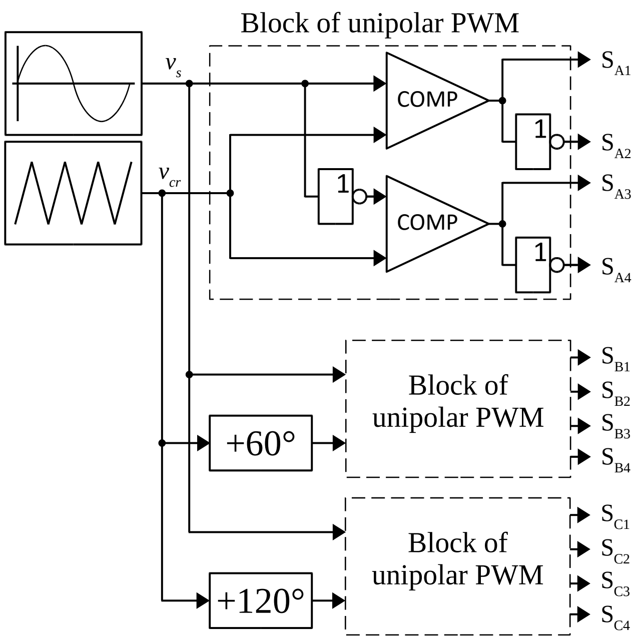

Fig. 2: Three-cell PS-PWM modulation method diagram.

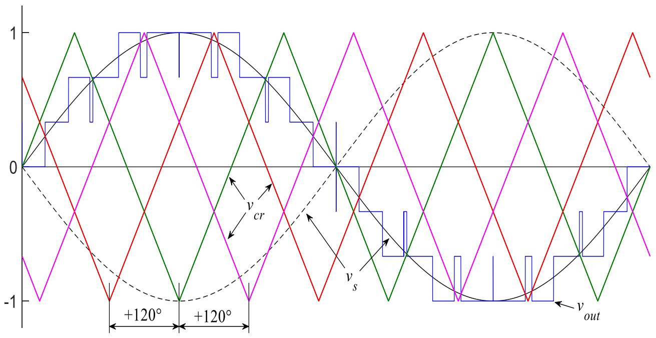

Fig. 3: Three-cell (seven-level) PS-PWM output waveform.

IV. FAUL-TOLERANT OPERATION

A very interesting feature of the CHB multilevel converter is the ability to operate even in case of any power cell failure. The main reason is that the CHB converters have a modular and easily extendable structure and also have several redundant switching states. This allows reducing the machine stop to a minimum.

In general, several types of faults can occur in power converters. Firstly, a failure in dc-link (dc-link capacitor short-circuit, dc-link short-circuit to ground), line-to-line short-circuit or short-circuit to ground at the converter output, or failure of the switching device (short-circuit or open circuit).

Fault-tolerant operation requires to diagnostic the type of fault and where it has occurred as soon as possible. The most appropriate way how to detect faults is to monitor voltage and current across all the components (dc-link, switching device, load). The main drawback is the high cost of the diagnostic equipment and a large number of components. A more efficient way of detecting faults is by measuring voltage and current on the load. The advantage is lower cost and number of measuring components, but the main drawback is the detection dynamics which depend on the type of load.

Fault detection methods are analysed in [18]. The auxiliary switch is connected to each H-bridge (Fig. 4) and can bypass the power cell in case of failure. This will reduce the

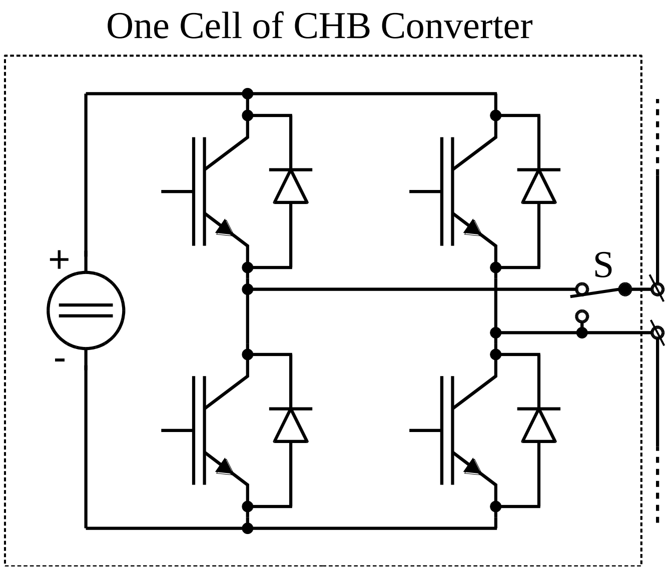

Fig. 4: One cell of CHB converter with auxiliary switch.

output voltage in the failed phase and the total output three-phase voltage will become unbalanced. However, even in this condition, the inverter can operate. An unbalanced voltage can be corrected in two ways. First, the converter bypassing the same number of power cells in the other phases. The three-phase output voltage becomes balanced again, but this will reduce the total power delivered by the converter. The second method is to change the angle of the control sinewave signal of each phase from the reference. Detailed analysis fault-tolerant operation of CHB converters is in [19].

V. CONDITION OF TEST SYSTEM

A CHB converter with six H-bridges per phase was chosen to powered medium-voltage motor for coolant pump. The converter can generate 13-level 6 kV line-to-line voltage with first harmonic frequency 300 Hz, which is required by the application. The modulation method for switching devices of the converter is based on phase-shifted of carrier signals for each cell. The most optional is variant with a 60° offset (360°/6 = 60°), which achieves the lowest distortion of the output voltage. The frequency of the triangle carrier signal is 1200 Hz.

The converter was simulated for operation under normal and fault conditions with a constant speed of the coolant pump motor, which is replaced by an RL circuit with a resistance of 0.5 Ω and an inductance of 1 mH.

VI. SIMULATION UNDER NORMAL CONDITIONS

Fig. 5 shows voltage in one phase and Fig. 6 show all line-to-line voltage in kV. These figures demonstrate all the benefits of using a CHB multilevel converter against common two-level converters. In the Fig. 5, there is the phase voltage of the five-level converter, it is apparent that the output voltage waveform is closed to sinusoidal waveform. It can be observed that there will be less distortion of voltage, an improvement in THD and reduced *dv*/*dt*. This reduces the stress on the motor bearings and windings and reduces pulsation on the motor shaft. Total harmonics distortion (THD) reaches a value of 0.9984. In comparison with the typical two-level converters, there is significantly smaller THD. Typical THD value for a classic two-level converter reaches a value of 0.882.

In Fig. 7 a spectrum of all harmonics is shown. The first harmonic is dominant and the other harmonics are very

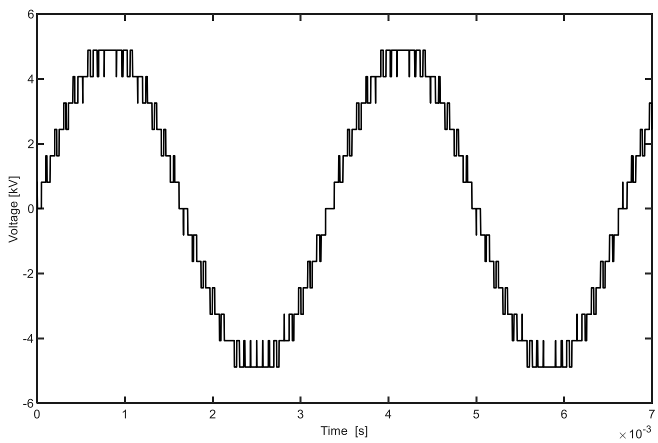

Fig. 5: Phase voltage of six cell (13-level) CHB converter.

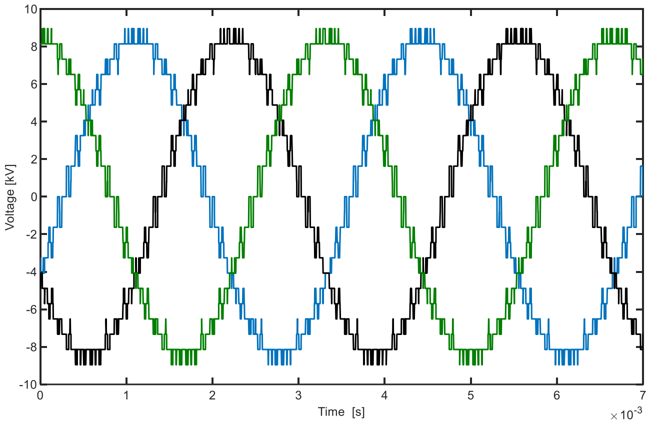

Fig. 6: Line-to-line voltage of six cell (13-level) CHB converter.

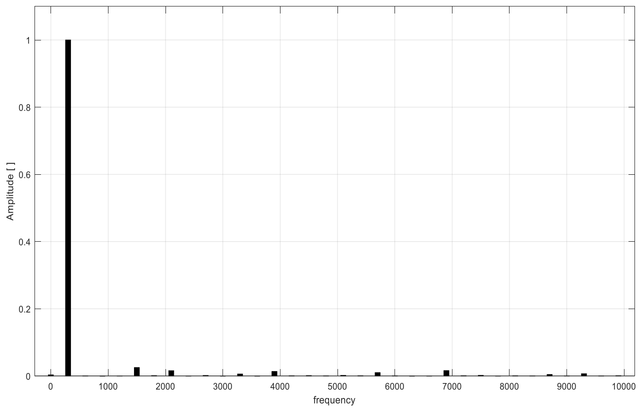

Fig. 7: Harmonic spectrum analysis of output voltage.

small, which is a great advantage of CHB multilevel converters. Other harmonics than the first do not transmit power, they only warm the windings and cause torque ripple.

VII. Simulation under Fault Conditions

To demonstrate the great benefit of a cascaded H-bridge multilevel converter, it is simulated the operation with some faulty power cells. Fig. 8 illustrates the waveform of the inverter voltage wherein phase *A* two power cells are in a fault condition and phase *B* one cell is in a fault condition. Phase *C* is in normal operation without failure of any cells. Cell disorders are resolved by bypassing, producing

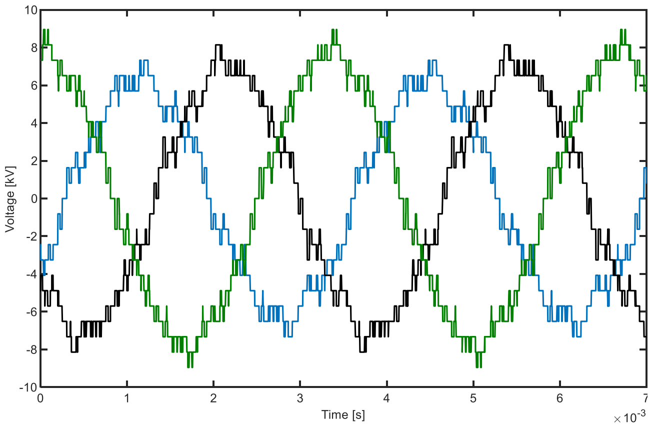

Fig. 9: Line-to-line voltage of six cell (13-level) CHB converter operation under fault condition.

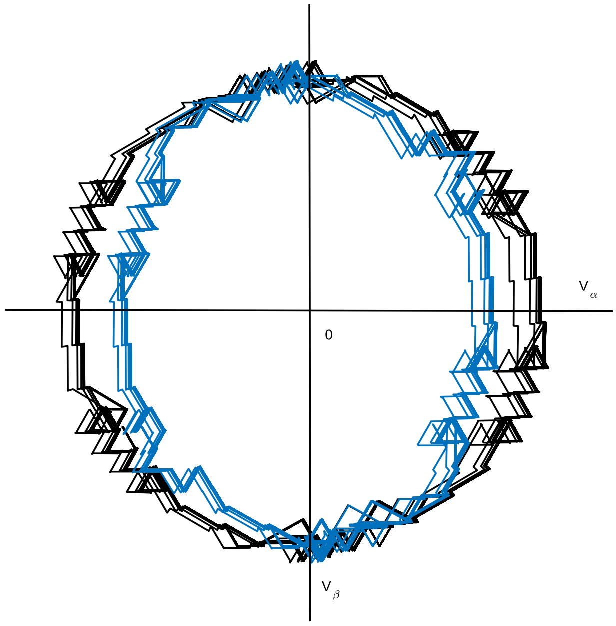

Fig. 8: Components of stator voltage V_s in the stationary $\alpha\beta 0$ reference frame.

unbalanced line-to-line voltages.

The failure has an interesting impact on the V_α and V_β components of the motor stator voltage V_s, which is illustrated in Fig. 9. The black spline is the voltage V_s under normal condition and the blue spline is the voltage V_s changes most, where the length is reduced. The resulting spline is no longer a circle but an ellipse with a slight left turn. However, this change in V_α voltage has little impact on open-loop motor control.

Fig. 10 compares the moments under normal condition (black line) and fault condition (blue line). It can be seen from the figure that the motor torque drops slightly when the pump is still able to operate.

As mentioned above, even if more than one power cell fails, the converter can still be operated, which is a great advantage of the selected converter topology.

VIII. Conclusion

This paper has presented a multi-level converter with cascaded H-bridge to control a power cooling pump.

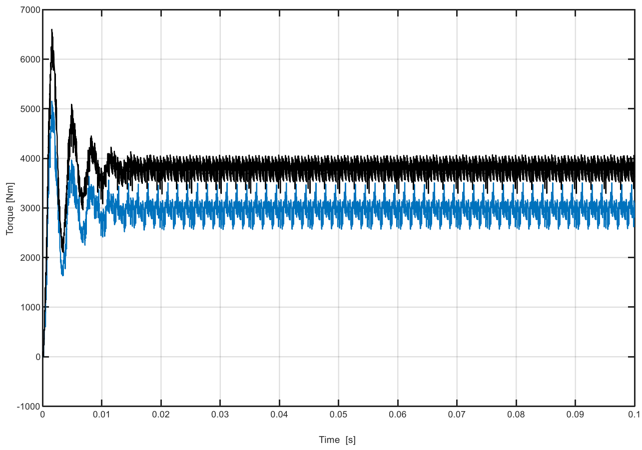

Fig. 10: Torque of motor.

CHB multilevel converters are used for example to control medium-voltage motors energy, conversion, and active power filtering. For the simulation, a 13-level CHB converter was selected in operation under normal conditions and in a fault condition. The motor was controlled in an open-loop. In normal operation, the advantages of using multi-level converters, in general, are evident. In normal operation, the advantages of using multi-level converters, in general, are seen. The output voltage waveform is closed to the sinusoidal waveform resulting in a significant improvement in the motor voltage distortion. A great advantage is also the ability to operate during a fault condition, whereby a faulty power cell can be replaced during a fault which reduces stop times of the machine. A simulation in this state showed that the converter is able to operate even during the failure of several power cells. There is only a slight decrease in line-to-line voltage and machine torque.

ACKNOWLEDGMENT

This research work has been carried out in the Xxxxx Xxxxx Xxxxx Xxxxx Xxxxx Xxxxx Xxxxx Xxxxx (XXXXXXX). Authors gratefully acknowledge financial support from the Xxxxx Xxxxx Xxxxx, Xxxxx Xxxxx Xxxxx Xxxxx Xxxxx Xxxxx Xxxxx Xxxxx (XXXXXXXXXX).

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