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Comparison of Reliability in Modular Multilevel Inverters

Abstract. *This paper studies the reliability of modular inverters with Half-Bridge and Full-Bridge cells. To calculate their reliability Markov Chain which models a sequence of random variables has been used. Therefore two main methods of reliability enhancement will be compared. Selecting one of these methods to have a fault tolerant system is based on the number of phase voltage levels. Finally, it can be concluded that, modular inverters with HB cells will have a better reliability compared to the inverters with FB cells.*

Streszczenie. *W pracy analizowana jest niezawodność modularnego przekształtnika z celkami typu półmostek i cały mostek. Do analizy użyto łańcucha Markova. Porównano też dwie metody poprawy niezawodności - jako kryterium przyjmując tolerancję błędu. Stwierdzono przewagę układów wykorzystujących półmostek. (**Porównanie jakości dwóch przekształtników modularnych**)*

Keywords: Modular multilevel inverter, FB and HB cells, Markov Chain, Reliability.
Słowa kluczowe: przekształtnik modularny, półmostek, łańcuch Markova.

Introduction

Nowadays, multilevel voltage source inverters offer several advantages compared to their conventional two-level inverters. In these inverters, by synthesizing several levels of dc voltages, the staircase output waveform is produced. The structure of this waveform leads to achieve higher output voltage and lower stress on power switches. Furthermore, by increasing the levels of output voltage, the waveform contains lower harmonic contents and will eventually approach a desired sinusoidal waveform that will lead to reduce the requirements of output filter.

Therefore multilevel inverters have been selected as a preferred power inverter topology for high voltage and high power applications [1, 2, 3].

The development of multilevel inverters can be divided into two issues, power circuit topology and the switching strategy. For circuit topology there are three main types: Diode Clamped type, Capacitor Clamped type, and finally, Modular type [3].

Utilizing of Diode Clamped types, with a number of levels larger than three, is not recommended. This is due to capacitor voltage balancing and also high voltage stress on three clamping diodes.

Furthermore, in this type of inverters, the number of clamping diodes is quadratically related to the number of levels, which will be dramatically increased by increasing the number of levels.

Capacitor clamped (Flying capacitor) types do not require additional clamping diodes and also provides redundant switching states that can be used to control the capacitors charge. Nevertheless, larger structures require relatively high number of capacitors and some circuits are also required to initialize capacitors charge. Furthermore, the large numbers of capacitors are either more expensive or bulky than clamping diodes in multilevel diode-clamped inverters [4, 5].

Another disadvantage of these two types of inverters is their non modularity which is more difficult in inverters with a high number of levels. In other words, these two types cannot be scaled to different power and voltage levels using the same hardware [3].

Modular Multilevel Inverter Topologies

a. Comparison of structures

Since power circuit of Modular type inverters are composed of an arbitrary number of identical cells, to have different voltage levels, no additional central component is necessary. Therefore in these types of inverters, scaling to different voltage levels will be done by varying the number of cells, only [3, 4, 5].

Depending on the structure of their cells, Modular inverters can be divided into two categories, one category has Full-Bridge cells, and the other has Half-Bridge or bidirectional cells. The structure of these cells has been shown in figure 1.

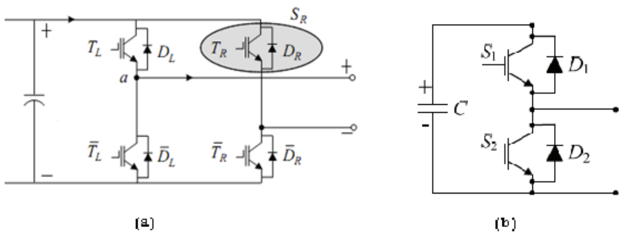

Fig.1. Cell structure of modular multilevel inverters, (a) FB cell, (b) HB cell.

In modular inverters with FB cells, separate and isolated dc sources are required which lead to have large transformers with high coupling capacitance. It should be noted that this capacitance causes very high EMC-disturbing current peaks[3, 6]; Since in Modular inverters with HB cells separate and isolated dc sources are not needed, this expensive transformer will not be required that is an important advantage compared to the Cascade FB inverters. Table 1, has compared the number of components in multilevel topologies.

Table 1. Comparison of power component requirements in multilevel modular topologies

Structure of cells	FB	HB
Number of switches	6(N-1)	6(N-1)
Number of clamping diodes	0	0
Number of dc link capacitors	3(N-1)/2	3(N-1)
Number of balancing capacitors	0	0
Total	15(N-1)/2	9(N-1)

As shown in figure 2, to synthesize the same number of voltage levels, the least number of total main components belongs to inverters with FB cells.

b. Comparison of Reliability

In Diode-Clamped and Flying-Capacitors topologies, occurring a failure in each switch will lead to fail the entire system. But in Modular inverters, because of redundant switching states, the failure of a switch can be compensated except in the case of an upper or lower voltage level which there is no redundant switching state for them.

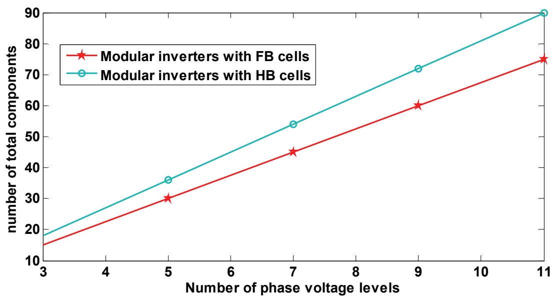

Fig.2. Comparison of power components in modular multilevel inverters.

Furthermore, since the output voltage of these two types of inverters is distributed uniformly among cells, redundant cells can be integrated.

Therefore, in the next section the reliability of inverters with HB and FB cells has been calculated and compared based on two main suggested methods.

It should be noted that in inverters with three phases, by occurring a switch failure, reconfiguration of the structure or varying the expected voltage levels of the phase voltages should be similar in phase legs. Otherwise, the line voltage of the inverter won't be desirable.

Fault Tolerant Modular Multilevel Inverters

a. Definition of Reliability and MTTF

Representing system failure in a probabilistic way is attractive because it naturally accounts the uncertainty. To make such representation, the process behavior is considered as a random variable that takes its values from a finite state space corresponding to the possible process states. In the case of finite or countable state space, Markov processes are represented by a graphic called Markov Chain which models a sequence of random variables [7].

It should be noted that these calculations have been done by assuming $\lambda_0 = 10^{-7} h^{-1}$ (failure rate of each switch). Other parameters are defined as:

F(t): Probability that the component will fail at or before time t, which is the cumulative distribution function.

f(t): Momentary rate of probability of failure at time t, like any density function.

The reliability function, that is the probability of success, is the complement of F(t) [7]:

(1) $$R(t) = 1 - F(t)$$

It should be noted that F and f are related through

(2) $$F(t) = \int_0^t f(\tau)d\tau \quad , \quad f(t) = \frac{dF(t)}{dt}$$

Another significant definition is the mean time to failure (MTTF), which in general is the expected life of a non-repairable product. In any case, the MTTF is a measure of the centre of a life distribution. Furthermore, the bigger MTTF leads to the smaller probability of finding a failure. Therefore it can also be evaluated to choose the topology with the highest reliability [8].

It should be appreciated that the analysis of the MTTF confirms the previous result of calculations for reliability. This parameter is defined as:

(3) $$MTTF = \int_0^\infty t f(t)dt$$

By considering equations (1) and (2), it can be concluded that:

(4) $$MTTF = \int_0^\infty R(t)dt$$

b. Inclusion of Redundant Cells

The inclusion of the redundant cells that is the result of uniform distribution of voltage among cells will increase fault tolerance of modular inverters. This also results an increase the number of cells (1 and 2 cells, respectively, for FB and HB cells) which deliver zero voltage at their output during operation. In the event of a cell failure, this fault will be detected and the defective cell will be shorted out. This provides fail safe functionally; therefore, the inverter remains at work without any interruption and operates with nominal output voltage [3, 9].

Since this method do not change the number of levels by occurring failure, it is recommended for inverters with low number of levels.

Figure 3 has shown the Markov Chain for modular inverters with FB cells.

In this chain, in the first state, there is no failure. By occurring one failure, system enters into the second state. In this state the defective cell has shorted out and the redundant cell will be replaced. Therefore an N level inverter can even have N level voltage levels. Finally, by occurring second failure, the inverter cannot remain at work, and will fail.

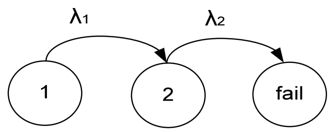

Fig.3. Markov Chain modelling of inverter with FB cells

Therefore the equations to calculate this reliability are:

(5) $$\lambda_1 = \left(\frac{N-1}{2} + 1\right)\lambda_{FB\ cell} = 2(N+1)\lambda_0$$

(6) $$\lambda_2 = \left(\frac{N-1}{2}\right)\lambda_{FB\ cell} = 2(N-1)\lambda_0$$

Furthermore:

(7) $$\frac{dP_1}{dt} = -\lambda_1 P_1$$

Therefore:

(8) $$P_1 = e^{-\lambda_1 t}$$

and in a similar way:

(9) $$\frac{dP_2}{dt} = \lambda_1 P_1 - \lambda_2 P_2$$

(10) $$P_2 = \left(\frac{N-1}{2}\right)(e^{-\lambda_2 t} - e^{-\lambda_1 t})$$

And finally:

(11) $$R(t) = P_1(t) + P_2(t)$$

Then:

(12) $$R(t) = e^{-\lambda_1 t} + \left(\frac{N-1}{2}\right)(e^{-\lambda_2 t} - e^{-\lambda_1 t})$$

The Markov Chain for Modular inverters with HB cells has been shown in figure 4. Similar the previous chain, in the first state, there is no failure in the system. By occurring one failure in one of the switches in the upper (or lower) half of each phase leg, system enters into the second (or third) state. In these states the defective cell has shorted out and the redundant cell of the corresponding half phase leg will be replaced.

In these conditions, if second failure will be in the same half of each phase, there is no other redundant cell, and the entire system will fail. However, if the second failure will be in the other half of each phase, the other redundant cell will be used and the system enters into the state 4, which is similar to state 2 and 3. Therefore, by occurring one failure (or two failures in half of each phase legs) an N level inverter can even have N level voltage levels.

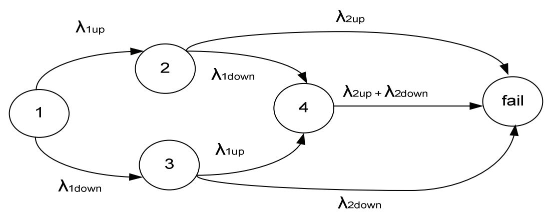

Fig.4. Markov Chain modelling of Modular inverter with HB cells

The equations are:

(13) $$\lambda_{1up} = \lambda_{1down} = \left(\frac{N-1}{2}+1\right)\lambda_{HB\ cell} = (N+1)\lambda_0$$

(14) $$\lambda_{2up} = \lambda_{2down} = \left(\frac{N-1}{2}\right)\lambda_{HB\ cell} = (N-1)\lambda_0$$

Furthermore:

(15) $$\frac{dP_1}{dt} = -(\lambda_{1up}+\lambda_{1down})P_1$$

(16) $$P_1(t) = e^{-(\lambda_{1up}+\lambda_{1down})t}$$

And:

(17) $$\left(\frac{dP_2}{dt}\right) = -(\lambda_{2up}+\lambda_{1down})P_2 + \lambda_{1up}P_1$$

(18) $$P_2 = \left(\frac{N-1}{2}\right)(e^{-(\lambda_2+\lambda_1)t} - e^{-2\lambda_1 t})$$

And:

(19) $$\frac{dP_3}{dt} = -(\lambda_{1up}+\lambda_{2down})P_3 + \lambda_{1up}P_1$$

(20) $$P_3 = P_2$$

And:

(21) $$\frac{dP_4}{dt} = -\left(\lambda_{2up}+\lambda_{2down}\right)P_4 + \lambda_{1down}P_2 + \lambda_{1up}P_3$$

(22) $$P_4(t) = \frac{(N-1)^2}{4}(e^{-2\lambda_1 t} + e^{-2\lambda_2 t}) - \frac{(N-1)^2}{2}e^{-(\lambda_1+\lambda_2)t}$$

Then:

(23) $$R(t) = P_1(t) + P_2(t) + P_3(t) + P_4(t)$$

Considering figure 5, it can be concluded that in the first method, inverters with HB cells will have higher reliabilities. Furthermore, by increasing the number of levels, because of increasing the probability of occurring failure, the reliability will be decreased.

c. Reduction the Number of Levels

Because of redundant switching states, the effects of failure can be compensated, except in the case of outer voltage levels.

For example by assuming N=5, inner and outer voltage levels are {-1, 0, 1} and {-2, 2}, respectively. Also the number of cells for FB and HB structures in modular inverters is 2 and 4, respectively.

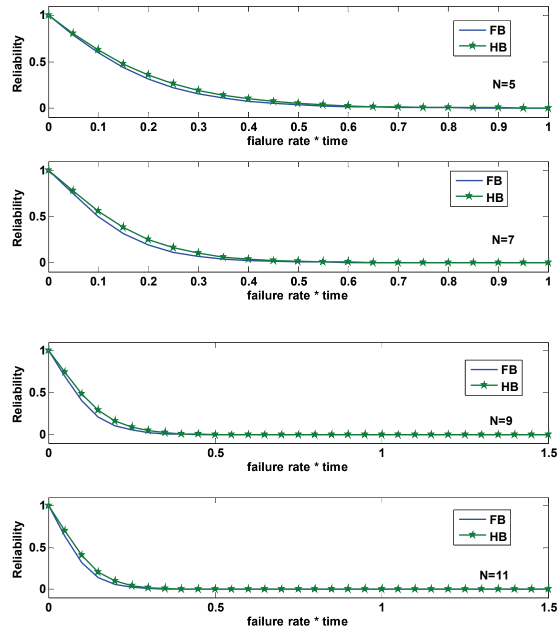

Fig.5. Comparison of reliabilities among Modular inverters (in the first method)

In modular inverters with HB cells, by occurring a failure in one of the switches in the upper (or lower) half of each phase, possibility of creation of voltage levels 2 (or -2) will be removed.

In a similar way, for a modular inverter with FB cells, by occurring failure in each of switches of two cells, only creation of the three voltage levels of the other cell is possible.Therefore, it can be concluded that by occurring failure in each switch of the Modular inverters, reaching to all voltage levels is impossible, while reaching to N-2 voltage levels is possible. So the reliability of these two topologies in converting the number of voltage levels from N to N-2 has been studied. Since reduction the levels from N to N-2 in lower number of levels can lead to an extreme reduction of output voltage, this method is only recommended for inverters with high number of level. It should be noted that Markov Chain for this method is similar the previous one, except in the calculation of failure rates.

In the chain of modular inverters with FB cells, by occurring one failure, system enters into the second state. In this state, an N Level inverter can have only N-2 voltage levels. Finally, by occurring second failure, the inverter cannot remain at work, and will fail. Therefore, the equations to calculate failure rates between states are:

(24) $$\lambda_1 = \left(\frac{N-1}{2}\right)\lambda_{FB\ cell} = 2(N-1)\lambda_0$$

(25) $$\lambda_2 = \left(\frac{N-1}{2}-1\right)\lambda_{FB\ cell} = 2(N-3)\lambda_0$$

For HB cells, Similar the previous chain, in the first state, there is no failure in the system. By occurring one failure in one of the switches in the upper (or lower) half of each phase, system enters into the second (or third) state.

In these conditions, if second failure will be in the same half of each phase, the entire system will fail. However, if the second failure will be in the other half of each phase, the system enters into the state 4, which will be at work by N-2 levels, such as state 2 and 3.

The failure rates are:

(26) $$\lambda_{1up} = \lambda_{1down} = \left(\frac{N-1}{2}\right)\lambda_{HB\ cell} = (N-1)\lambda_0$$

(27) $$\lambda_{2up} = \lambda_{2down} = \left(\frac{N-1}{2}-1\right)\lambda_{HB\ cell} = (N-3)\lambda_0$$

When the maximum number of level reduction is limited to 2, the reliability of modular inverters with HB cells will be more than HB inverters as shown in figure 6. Furthermore, the comparison of MTTF of these two inverters is shown in figure 7. As it can be seen, the results of figure 6 will be confirmed.

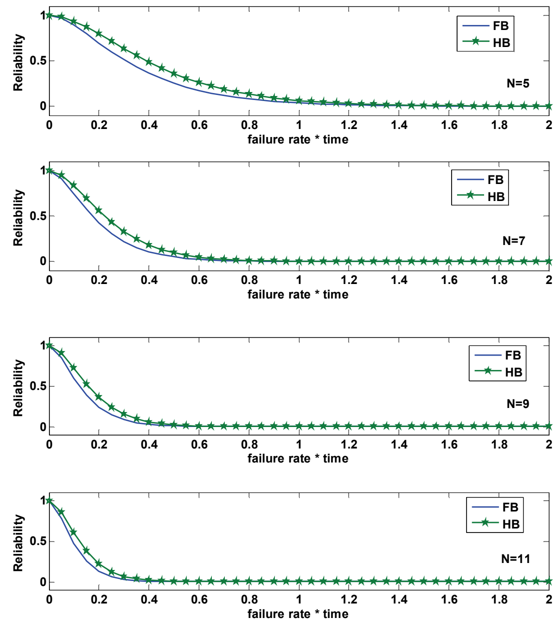

Fig.6. Comparison of reliabilities between Modular inverters (in the second method)

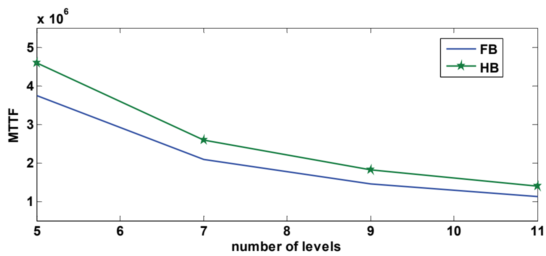

Fig.7. Comparison of MTTF between Modular inverters

One important assumption in the calculation of this section is based on balancing of phase voltages of the inverter with respect to the zero level. In other words by removing this assumption, the voltage levels of phase voltage can reduced to an even number of levels. So, the new probabilities of having N-2 and N-1 level can be calculated.

Therefore, in modular inverters with HB cell, occuring a failure in the up or down half of phase will be similar. Furthermore, in FB inverters, occuring a failure in each switch of the cell will not lead to bypass condition for the entire cell. Considering figure 8, it can be concluded that in FB cells, conduction path of the S_R and $\bar{S}_L$ creates the negative level (-1), and the conduction path of the two others creates the positive level (+1). Switching states of this cell has presented in table II [3]. By occuring a failure in one of the pairs of each cell, two switches of the defected pair will become bypass and the other pair remains at work. For instance if a failure has occurred in switch S_R, S_R and $\bar{S}_L$ will become bypass and $\bar{S}_R$ and S_L remains at work. This leads to have only 2 levels {0, -1} at the output voltage of the cell, instead of the three levels {-1, 0, +1}.

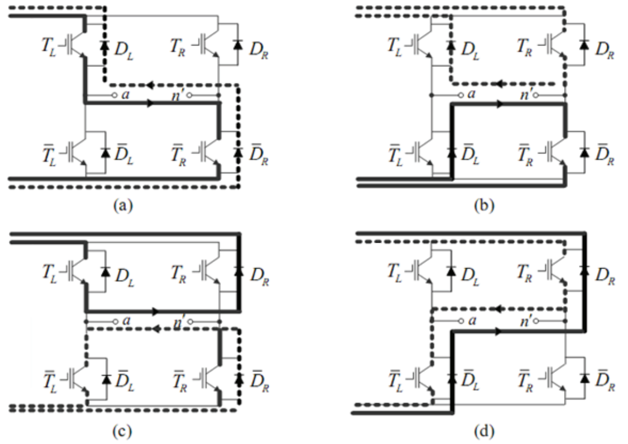

Fig.8. Conductoin path of the single-phase FB cell: (a) positive, (b, c) zero, and (d) negative states.

Table 2. Switching states of the FB cell

state	S_L	S_R	$\bar{S}_L$	$\bar{S}_R$
Positive (+1)	1	0	0	1
Zero (0)	1	1	0	0
	0	0	1	1
Negative (-1)	0	1	1	0

The Markov Chain for modular inverters with HB and FB cells has been shown in figure 9. The faiure rate of each pair which creates the levels of {+1, -1}, can respectively be presented by λ_{i1} and λ_{i2}. It should be noted that i represents i^{th} cell and:

(28) $$\lambda_{i1} = \lambda_{i2} = \lambda = 2\lambda_0$$

The number of pairs in modular inverters with FB and HB cells, is twice and equal the number of cells which is finally (N-1), respectively. Similar the previous chains, the first state represents there is no failure in the system. Then by occuring one failure, system enters second state, which have N-1 voltage levels. Occuring second failure lead to enter the system into third state, which has N-2 voltage levels. Therefore the probability of second and third states represents the probability of having N-1 and N-2 levels in phase voltages, respectively.

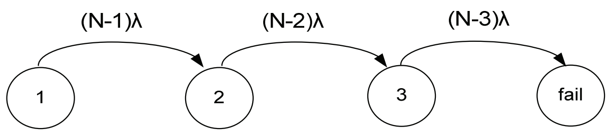

Fig.9. Markov Chain Modelling for both of modular multillevel inverters

Since assumption is based on the maximum number of level reduction is limited to 2, by occuring third failure the system will fail. Figures 10 and 11 show the reliabilities of modular inverters, when the maximum number of level reductions is limited to 1 and 2, respectively. Furthermore, comparison of MTTFs in figure 12, confirms the results of figure 11.

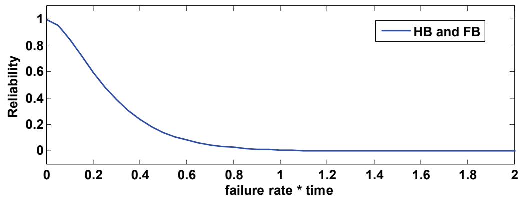

Fig.10. Comparison of reliabilities between modular inverters

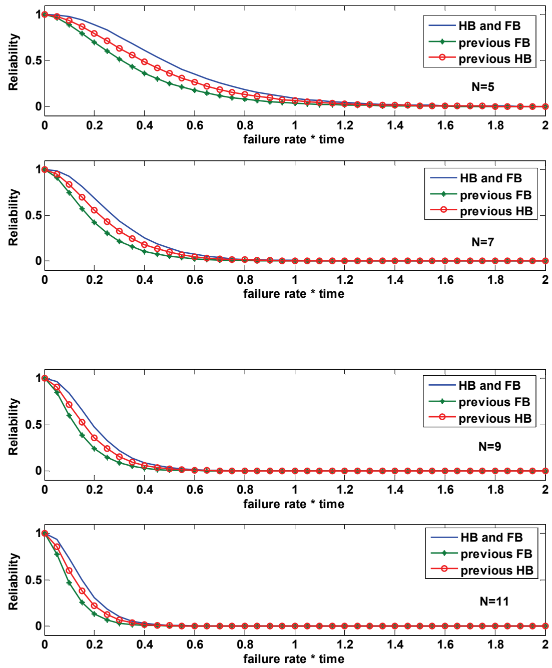

Fig.11. Comparison of reliabilities between modular inverters

Considering figure 11, it can be concluded that by removing the assumption of phase voltage balancing with respect to the zero level, the reliability of both types of inverters will be equal. Furthermore, it can be concluded that higher reliabilities will be achieved.

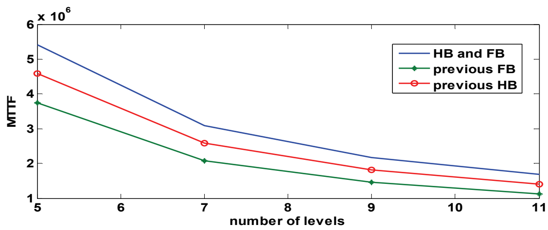

Fig.12. Comparison of MTTF among Modular inverters

Conclusion

Circuit topology of inverters can be divided into three types. The first two types, Diode Clamped and Capacitor Clamped types which are not scalable, are not recommended for high level inverters. Therefore the other two types which are named Modular inverters, with advantage of scalability, have been studied.The computed reliability by Markov Chain, for both types of Modular inverters has been compared. To have an accurate comparison, two methods have been studied.

In the first method modular inverters with FB and HB cells, respectively have one and two redundant cells per each phase leg; while occurring a failure, the defected cell will be replaced by the redundant cell. By this method inverters with HB cells have a better reliability compared to the inverters with FB cells.

Second method is based on reduction the voltage levels of phase voltages and it has been assumed that the maximum reduction number of levels will be 2.

It should be noted that if phase voltage balancing with respect to the zero voltage will be considered as an important criterion, voltage levels can only have an odd number of levels, such as N and N-2. Otherwise, voltage levels can have an even number of levels such as N-1.

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