Enhanced switching converter for photovoltaic systems: performance analysis and simulation

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ABSTRACT

This paper focuses on reducing switching losses and stresses in photovoltaic (PV) inverters by introducing a new five-level hybrid T-type multilevel inverter (T-MLI). The proposed topology was designed and simulated using physical security information management (PSIM) software and validated using one year of solar radiation and temperature data to account for seasonal variations. The proposed inverter was also experimentally implemented through hardware development, and its performance was evaluated under different load conditions. Under nonlinear load conditions, the results demonstrate that the proposed T-MLI reduces total harmonic distortion (THD) to 3.8%, reduces voltage stress on the switches, improves direct current (DC)-link utilization, and enhances the overall efficiency of the inverter system compared with the traditional topology.

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1. INTRODUCTION

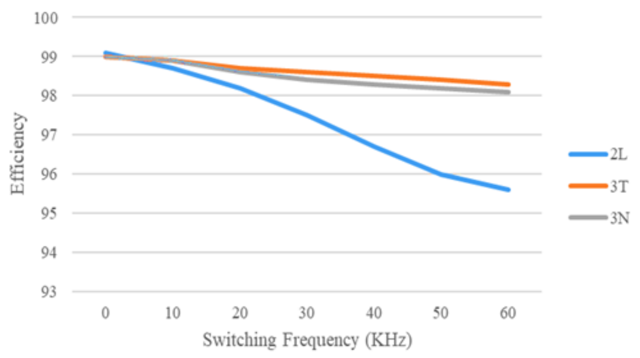
Because of the imminent depletion of fossil fuels and rapid global changeover to clean energy, photovoltaic (PV) generation is an essential member of green power generation [1]. For a grid-connected PV generation system, a PV inverter is utilized to convert direct current (DC) into high-quality alternating current (AC) while achieving high efficiency, reliability, and grid standard compatibility, and is crucial for system performance [2], [3]. There are several shortcomings, such as switching losses, a large number of components, harmonic distortions, and system cost in existing PV inverters, and they bring restrictions for practical usage.

For common PV inverters, there exist two types: a two-stage inverter and a high-switch-number multi-level inverter. Although these kinds of inverters possess a good output voltage waveform, these configurations lead to a large number of power switches, great switching losses, and complicated control methods [1]–[3]. By now, a single stage and a reduced number of switches inverter structures are the new tendency of PV inverters, which result in lower cost, less switching losses, and greater efficiency [4]–[6]. However, for these kinds of topologies, it is still a key and complex work to remain the high efficiency and stability under dynamic input conditions.

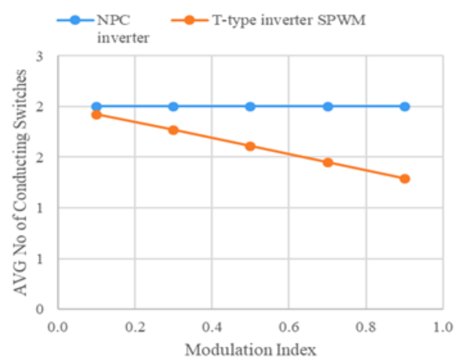
Recent research efforts on the design of power converters have involved a variety of promising techniques such as soft-switching and resonant structures to minimize the switching loss, harmonic emissions, and thermal stress. Zero voltage switching (ZVS) and zero current switching (ZCS), inductor-inductor-capacitor (LLC) resonant structure, and the series resonant structure can offer efficient performance [7]–[14]. In addition, many efficient and adaptable maximum power point tracking (MPPT) control methods have been presented to improve the dynamic responses for various irradiance variations [15]–[19]. Furthermore, single-stage zero-leakage transformers (ZLT) such as H5, H6, and the highly efficient and reliable inverter concept (HERIC) have been widely adopted; as have multilevel converter structures such as the neutral point clamped (NPC) inverter and the cascaded H-bridge (CHB) inverter [15]–[20]. While many such schemes were investigated and proved to be capable of realizing some specific goals, they suffered from various trade-offs. Despite this remarkable progress, a key research challenge for designers of low- and medium-power PV systems for rooftop and residential power production remains to be addressed, specifically: to develop high-efficiency, compact, single-stage inverter solutions with the lowest possible number of switches and passive components and robustness for dynamic behavior [21]–[23].

This article proposes a new single-stage grid-connected converter using a hybrid T-type multi-level structure, which reduces the number of components to enhance the utilization of DC-link voltage and lower the device voltage stresses. A more effective modulation strategy is carried out to achieve low harmonic distortions and switching losses. The performance is investigated using simulation for various conditions, compared with the other two topologies and summarized in terms of the total harmonic distortion (THD), efficiency, voltage regulation, and dynamic behaviors of the proposed configuration, which confirms its superiority.

Comparative analyses are also undertaken on the various inverter topologies in conjunction with switching losses, device count, and efficiencies, as shown in Figure 1. From Figure 1(a), it can be clearly seen that the proposed converter has higher efficiency in the high switching frequency range compared with the two-level and the NPC structure. This indicates that the switching losses are reduced. From Figure 1(b), it can find that the number of conducting devices of the T-type inverter is less than that of the NPC structure when the modulation index is increased; thus, conduction loss is reduced. On the other hand, the total number of switching devices and components of the proposed topology is less compared with that of some selected single-stage and NPC inverters, as is evident from Figure 2 [1], [3], [4], [9], [23].



(a)



(b)

Figure 1. A comparative analysis of (a) efficiency vs. switching frequency and (b) average number of conducting devices

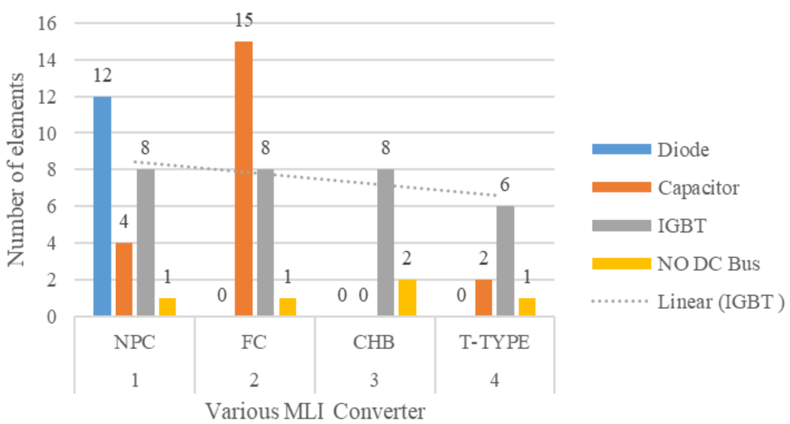


Figure 2. Comparison of device count

This article focuses on the performance analysis of the proposed system using simulation-based benchmarking with well-known existing multi-level topologies. THD, conversion efficiency, voltage regulation, and transient response of the system are used as performance indices by changing irradiance and load scenarios. The remaining sections are arranged as follows: section 2 converter background, section 3 proposed T-type multilevel inverter (T-MLI) coupled to PV system modelling and simulation, section 4 results and discussion, and section 5 conclusion of this research.

2. FIVE LEVEL T-TYPE MULTILEVEL INVERTER

MLIs, such as modular multilevel inverters (CHB), have the ability to synthesize multiple DC bus voltages into a single high-quality AC waveform. MLIs have become highly popular in grid-connected PV systems because they produce lower THD, less switching stress, less equated monthly installment (EMI). The existing studies address this problem by proposing reduced switch-count MLIs based on single-stage design. Single-stage designs employ the minimum possible active switching device and the number of stages in power conversion for less conduction and switching losses and enhance reliability. Minimizing the switches means reducing the total number of switching events, thus reducing power loss. The proposed reduced-switch MLI structure is compared with the 5-level inverter structure to demonstrate the merits in respect of output AC waveform quality and harmonic performance with variations of the solar irradiance and load circumstances so as to satisfy the requirement for connecting with the grid.

MLI topology in Figure 3 illustrates a five-level MLI with a split DC source comprising two capacitors (C1 and C2), and six switches [21], [24], [25]. Due to the 'T'-shaped structure of the main switching part, this T-MLI will utilize six controlled switching devices for five-level output voltages, which in turn leads to a reduction of switching devices and increases overall efficiency [1]–[6]. The proposed topology has the capability of generating 5 different levels output voltage, namely +Vdc, +Vdc/2, 0, Vdc/2, and Vdc. Table 1 shows the switching modes of the proposed T-MLI needed to obtain five-level voltage output. This table shows the operating states (on/off conditions) of the diodes and switches for producing each level output voltage; to prove it uses very few switching devices to generate this level voltage output [15], [22], [23]. Figure 4 illustrates the four operating stages of the five-level T-MLI, showing different switching combinations to generate the required output voltage levels. The highlighted paths indicate the current flow and conducting switches for each operating stage, enabling stepped five-level output voltage generation.

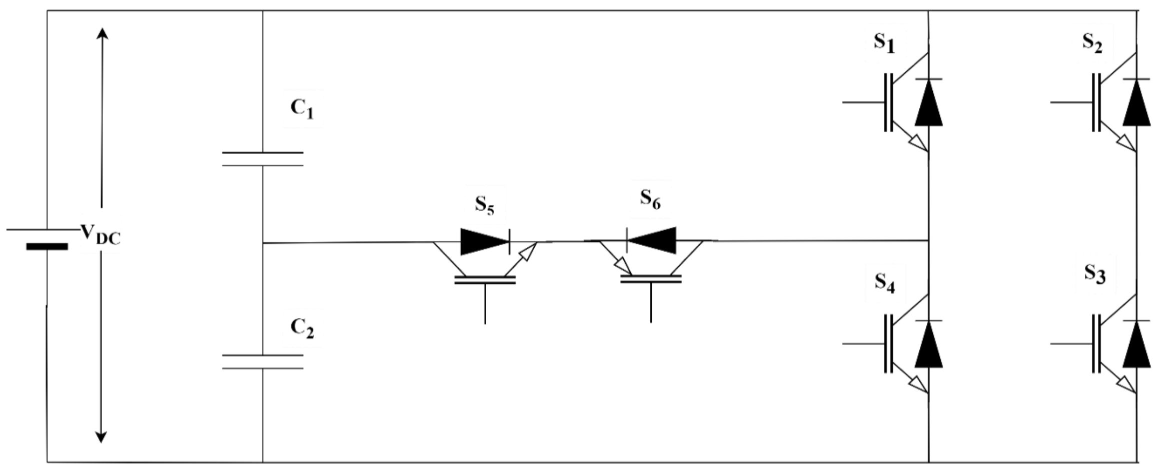


Figure 3. The five-level T-MLI topology along with its switching states

Table 1. The switching states for the five-level T-MLI

Output voltage	S1	S2	S3	S4	S5	S6	D5	D6
+Vdc	1	0	1	0	0	0	0	0
+Vdc/2	0	0	1	0	0	1	1	0
0	1	1	0	0	0	0	0	0
-Vdc/2	0	1	0	0	1	0	0	1
-Vdc	0	1	0	1	0	0	0	0

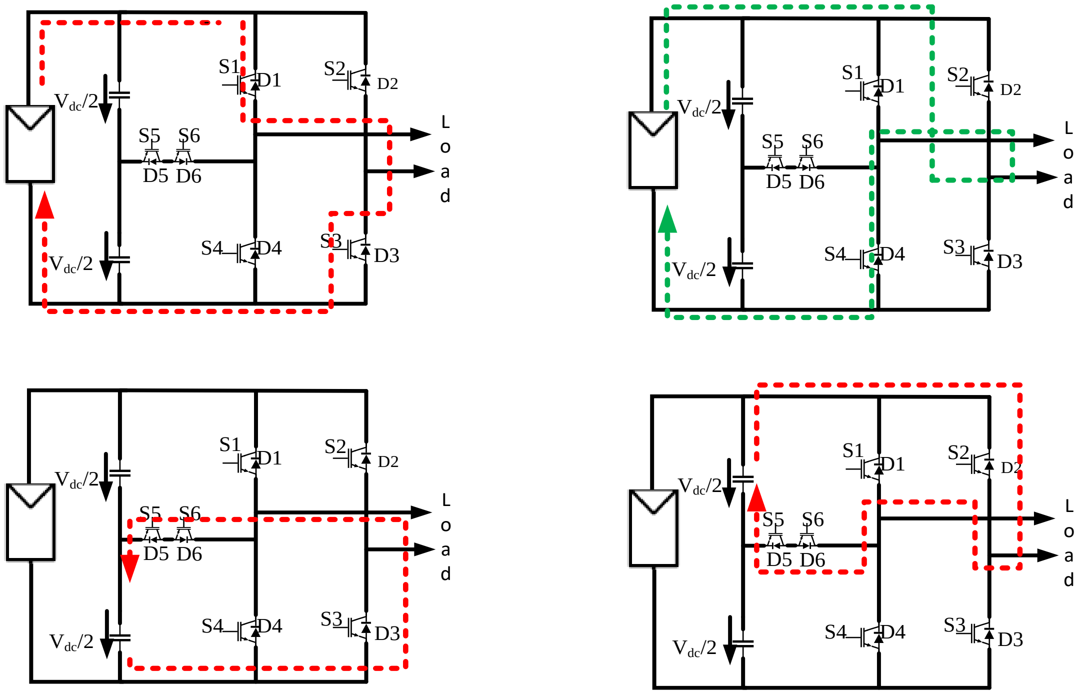


Figure 4. Five-level T-MLI operating stages

3. MODELING AND SIMULATION OF THE PROPOSED T-MLI WITH PV SYSTEM

Accurate solar system simulation considers irradiance, temperature, module efficiency, tilt angle, and site conditions. A 500 W PV module modeled in physical security information management (PSIM) used real irradiance and temperature data via a lookup table to emulate seasonal variations. The T-MLI was tested under these profiles to evaluate MPPT accuracy, control stability, and energy conversion efficiency.

3.1. Dynamic simulation of T-MLI with PV source without DC–DC converter

In the case of the T-MLI with a PV source without a DC-DC converter, the system represents a single-stage PV-integrated inverter in which the PV array is directly connected to the inverter DC-link without using an intermediate DC-DC conversion stage. The split capacitors establish the DC-link voltage and help maintain voltage balance during inverter operation. By the appropriate switching of switches, the inverter generates a multilevel AC output waveform, which is then filtered to reduce switching harmonics before supplying the load. Such a configuration is employed in the analysis to examine dynamic performance under varied conditions of irradiance and load, with significant focus on the PV electrical parameters, DC-link response, inverter switching dynamics, and the quality of the output power. Figure 5 shows a PV system integrated with a DC–DC boost converter and a five-level T-MLI connected to a load and a single-phase 230 V grid. The boost converter, controlled by MPPT, steps up and regulates the PV output to ensure optimal operation under varying irradiance and temperature conditions. The five-level T-MLI converts the regulated DC into low-THD AC and synchronizes with the grid for efficient power transfer.

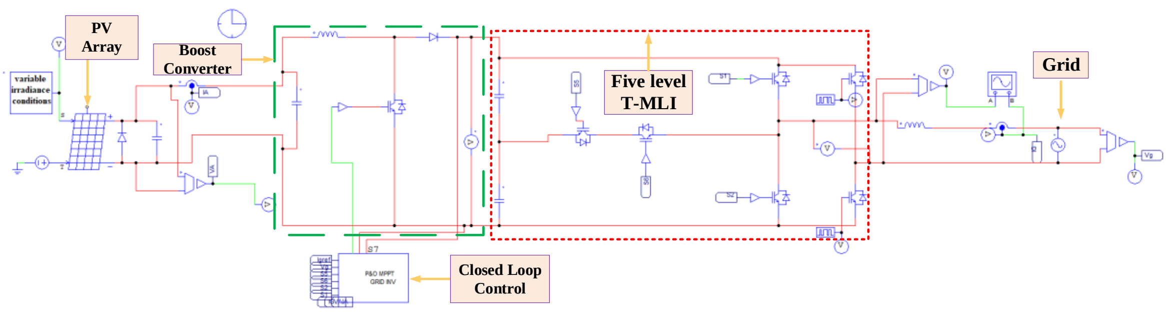


Figure 5. T-MLI with PV source with MPPT and grid connected

3.2. Dynamic simulation of T-MLI with PV source and MPPT control with grid

The T-MLI with PV source and MPPT control is a grid-connected system that converts PV DC power into synchronized AC output. The MPPT controller maximizes power extraction under changing irradiance and temperature, while the inverter and filter improve grid synchronization and power quality. Figure 6 shows the grid-connected PV system employing a coordinated control strategy in which the MPPT controller adjusts the operating point of the PV array to extract maximum available power under changing irradiance and temperature conditions, while the proportional-integral controller regulates the DC-link voltage to maintain power balance between the PV source and the inverter stage. The inverter current is synchronized with the grid through an appropriate synchronization mechanism, and the controller output is converted into PWM gating signals to drive the switches of the T-MLI, enabling sinusoidal current injection into the grid with low harmonic distortion and stable power transfer.

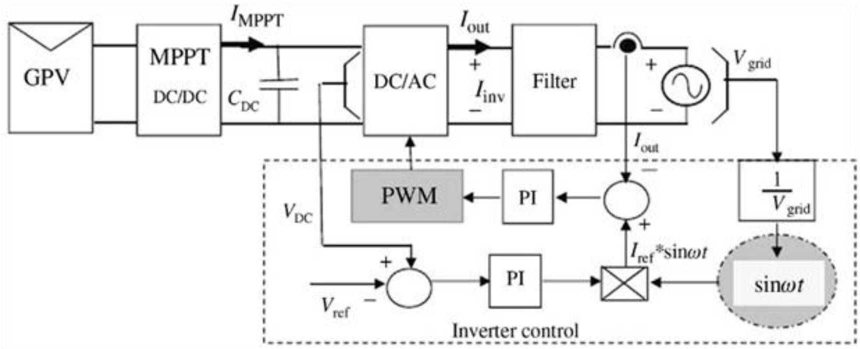


Figure 6. Block diagram of grid-connected PV system with MPPT control

3.3. Prototype hardware implementation

Figure 7 shows the experimental inverter hardware prototype and laboratory test bench, along with the corresponding gate pulse waveforms for the six inverter switches. The first part of the figure presents the developed inverter hardware setup, including the inverter switch module, gate driver circuit, control unit, and measuring instruments, while the second part presents the gate pulses generated for all six switches. The combined presentation of the hardware prototype and gate pulse waveforms provides a clear representation of the developed experimental setup and the switching signals applied to the inverter.

Figure 7. Experimental hardware prototype setup and gate pulse

4. RESULT AND DISCUSSION

In this section, results obtained and comparisons between several topologies discussed above, which were simulated in the previous section, are detailed as follows. For comparisons, of voltage total harmonic components of the load voltage and the load current are considered at the same load condition. It is noted that the DC-link voltage is maintained at a constant value for three topologies [1]–[5]. For the five-level T-MLI with phase disposition (PD) output voltage of the inverter, the voltage of the inverter was demonstrated as shown in Figure 8. From Table 2, it can be seen that for the two five-level inverter topologies (PD and alternative phase opposition disposition (APOD)), keeping the DC-link voltage nearly the same, and for APOD inverter THD (3.8%) and output voltage are slightly more and less than PD topology, respectively [17]–[20], [26], [27]. From Table 3, it is evident that the proposed converter keeps the output voltage approximately the same during solar power fluctuation.

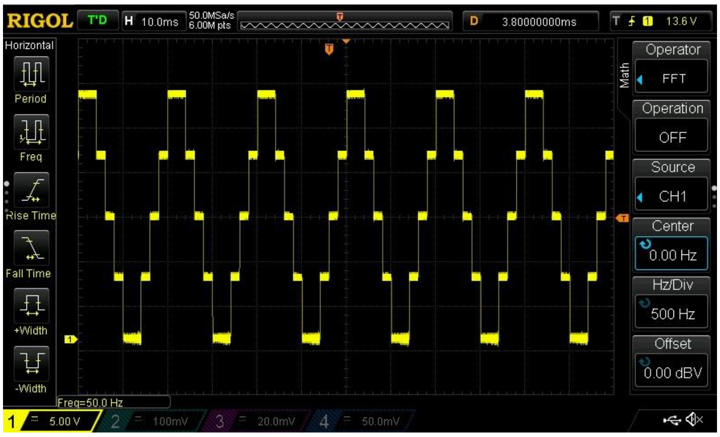


Figure 8. Output voltage five-level T-MLI

Table 2. THD and output voltage comparison for different topologies

Topology name	I_{THD} (%)	O_{ut}(V)	DC-link voltage(V)
Five-level (PD)	3.9	40	40
Five-level (APOD)	3.8	41	40

Table 3. Analysis of THD and voltage variation with irradiance

Irradiance (w/m^2)	Tracked power	V_{boost}	V_{rms}	I_{rms}	V_{THD} (%)	I_{THD} (%)
400	497 W	328 V	238 V	2.13 A	28	4.50
600	854 W	327 V	238 V	3.72 A	28.50	4.90
1,000	1,550 W	339 V	237 V	6.70 A	29	4.20

This result proved that the proposed converter presents a voltage regulation feature at the load side. While at lower irradiation, THD has a slight increase that is caused by lower input power and nonlinearity of the inverter at low-frequency switching [1], [6], [27]. The waveforms demonstrate as shown in Figure 9, system's response to dynamic conditions in irradiance, showing that the proposed converter provides good output voltage regulation and perturb and observe (P&O) MPPT strategy tracking max output power. Therefore, the proposed converter has industrial merits, such as reducing inverter cost because of lower levels of conversion and reduced component stress, and higher efficiency due to a smaller number of conversion levels and simpler topologies that are suitable for space-restricted applications like residential rooftop applications and can be employed in industrial and decentralized power generation applications.

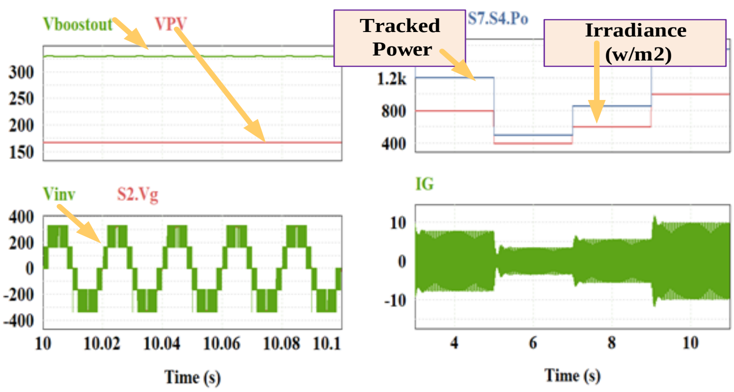


Figure 9. Tracked power, grid current, and inverter voltage

5. CONCLUSION

The performance of the proposed five-level reduced-switch inverter has been successfully validated for PV applications under both standalone and grid-connected operating conditions. The obtained results demonstrate that the proposed topology reduces the number of power switches and associated switching stress while maintaining satisfactory power quality. In grid-connected mode, a current THD of 3.28% is achieved at the point of common coupling, satisfying the harmonic requirements for PV grid integration. The topology also improves DC-link voltage utilization and reduces overall converter complexity. Furthermore, the boost converter integrated with the MPPT algorithm effectively extracts the maximum available power from the PV array under varying irradiation and temperature conditions, while the output filter suppresses switching harmonics and improves the quality of the injected current. Overall, the results confirm the suitability of the proposed inverter for PV grid-interfacing applications by providing reduced component count, improved power quality, and efficient energy conversion. Future work will focus on hardware implementation, grid-code compliance testing, and the development of intelligent adaptive control strategies for microgrid and distributed generation applications.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Rakeshkumar A. Patel	✓			✓	✓		✓	✓		✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [NNP], upon reasonable request.

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