

A COMPREHENSIVE REVIEW ON TEMPERATURE-BASED VARIABLE SPEED DRIVE CONTROL OF REFRIGERATOR COMPRESSOR MOTORS USING PHOTOVOLTAIC POWER

Mr. Shrikant Daulatrao Zilpe ¹

Ph.D. Research Scholar
Department of Electronics and Computer Science
PGTD, Rashtrasant Tukadoji Maharaj Nagpur University, Nagpur, India
zilpeshrikant@gmail.com

Dr. Archana Girish Shirbhate ²

Associate Professor
Department of Electrical Engineering
Anjuman College of Engineering & Technology, Nagpur, India
Archana.shirbhate@rediffmail.com

Dr. Jyoti B. Fulzele ³

Associate Professor
Department of Electrical Engineering
Jawaharlal Darda Institute of Engineering & Technology, Yavatmal, India
bhongade10@gmail.com

Abstract The rapid increase in global energy demand, coupled with the adverse environmental impacts of fossil fuel consumption, has intensified research into energy-efficient and renewable-powered refrigeration systems. Refrigeration accounts for a significant share of residential and commercial electricity consumption, particularly in developing countries with rising living standards and hot climatic conditions. Conventional refrigerator compressor motors operate at fixed speeds and rely on grid electricity, leading to high energy losses, frequent cycling, reduced compressor lifespan, and increased greenhouse gas emissions. In recent years, the integration of **temperature-based Variable Speed Drive (VSD) control strategies** with **photovoltaic (PV) power systems** has emerged as a promising solution to improve energy efficiency, operational stability, and sustainability of refrigeration systems. This review presents a comprehensive and critical analysis of temperature-controlled VSD-driven refrigerator compressor motors powered by solar photovoltaic energy. The paper examines the evolution of compressor motor technologies, principles of VSD control, temperature sensing and feedback mechanisms, PV system integration, power electronics interfaces, and system-level performance optimization. Emphasis is placed on recent research contributions reported in 2023, highlighting advancements in inverter design, maximum power point tracking (MPPT), energy storage coordination, and intelligent control algorithms.

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Comparative performance metrics such as energy savings, coefficient of performance (COP), thermal stability, cost effectiveness, and carbon emission reduction are discussed. Challenges related to intermittency of solar power, control complexity, reliability, and economic feasibility are also critically evaluated. The review concludes with future research directions focusing on artificial intelligence-based control, smart grid integration, and large-scale deployment of solar-powered variable speed refrigeration systems.

Keywords: Photovoltaic power, Variable Speed Drive, Refrigerator compressor motor, Temperature-based control, Energy efficiency, Solar refrigeration

1. Introduction

Refrigeration technology plays a vital role in modern society by supporting food preservation, healthcare, industrial processing, and thermal comfort. However, refrigerator systems are among the most energy-intensive household appliances, operating continuously throughout the year. Traditional refrigerator compressors are typically driven by single-phase induction motors operating at constant speed and controlled using on–off thermostatic switching. Such fixed-speed operation results in frequent start–stop cycles, high inrush currents, mechanical stress, temperature fluctuations inside the refrigerated space, and poor part-load efficiency. These drawbacks contribute to excessive electricity consumption and reduced equipment lifespan. With increasing concerns over climate change and energy security, improving the efficiency of refrigeration systems has become a global research priority.

Simultaneously, solar photovoltaic power has gained prominence as a clean and renewable energy source due to declining panel costs, improved conversion efficiency, and supportive government policies. Solar-powered refrigeration is particularly attractive in regions with unreliable grid supply and high solar irradiance. However, the intermittent nature of solar energy necessitates advanced power conditioning and control strategies to ensure reliable compressor operation. The integration of Variable Speed Drive technology with PV systems enables adaptive control of compressor speed in response to cooling load and available solar power, thereby maximizing system efficiency.

Recent studies published in 2023 demonstrate that temperature-based VSD control allows continuous modulation of compressor speed based on real-time thermal demand, eliminating inefficient on–off cycling and improving energy utilization (Kumar et al., 2023; Li & Zhang, 2023). When powered by photovoltaic energy, such systems can significantly reduce grid dependency and carbon emissions. This review consolidates recent research findings to provide a holistic understanding of PV-powered, temperature-controlled VSD refrigerator compressor systems.

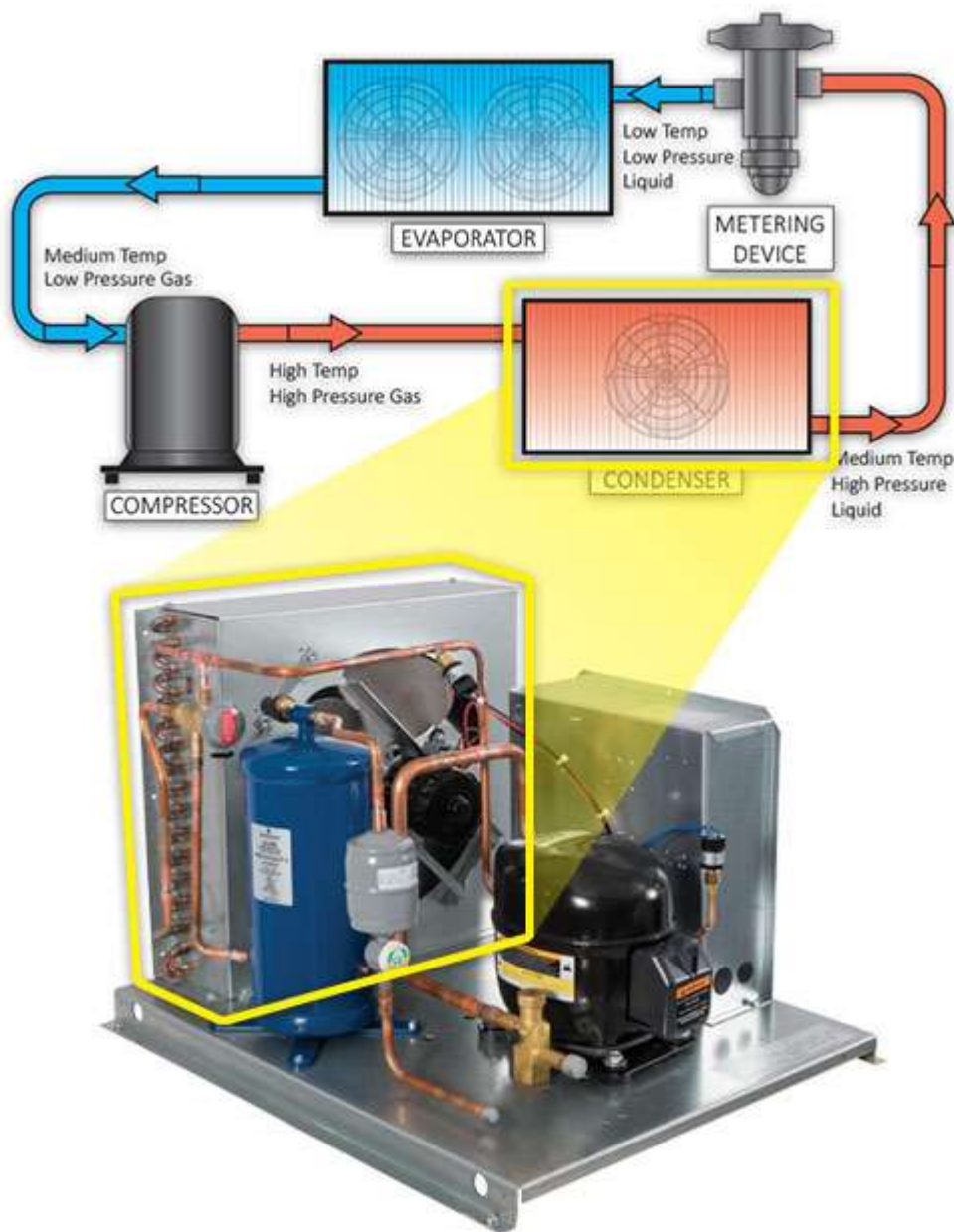


Figure 1. Schematic overview of a temperature-based variable speed drive (VSD) controlled refrigerator compressor system

2. Refrigerator Compressor Motors and Variable Speed Drive Technology

Refrigerator compressors are the core components responsible for circulating refrigerant and maintaining the desired cooling effect. Historically, reciprocating compressors driven by fixed-speed induction motors dominated domestic refrigeration due to their simplicity and low initial cost. However, fixed-speed motors are inherently inefficient under variable load conditions, as

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they operate at full speed regardless of cooling demand. Modern refrigeration systems increasingly employ brushless DC (BLDC) motors and permanent magnet synchronous motors (PMSMs), which are well suited for variable speed operation due to their high efficiency, precise controllability, and reduced losses.

Variable Speed Drives, also known as inverter drives, regulate motor speed by controlling the frequency and voltage supplied to the motor. In refrigeration applications, VSDs enable the compressor to operate over a wide speed range, matching cooling capacity to thermal load. Studies in 2023 report energy savings of 20–40% when VSD-controlled compressors replace fixed-speed systems (Singh et al., 2023; Park et al., 2023). Additionally, VSD operation reduces mechanical wear, lowers acoustic noise, and enhances temperature stability.

From a power electronics perspective, modern VSDs employ pulse-width modulation (PWM) inverters using insulated gate bipolar transistors (IGBTs) or silicon carbide (SiC) devices for higher switching efficiency. The integration of VSDs with PV systems further requires DC-link voltage regulation and bidirectional power flow capability when energy storage is used. The synergy between advanced motor technology and VSD control forms the foundation for high-performance solar-powered refrigeration systems.

3. Temperature-Based Control Strategies for Compressor Speed Regulation

Temperature-based control is central to achieving efficient variable speed operation in refrigerator compressors. Unlike traditional thermostatic control that merely switches the compressor on or off, temperature-based VSD control continuously adjusts compressor speed according to real-time temperature feedback from sensors placed inside the refrigerated compartment and at critical system points such as the evaporator and condenser. This approach ensures that cooling capacity precisely matches thermal demand, minimizing energy waste.

Recent research emphasizes proportional–integral–derivative (PID) control, fuzzy logic control, and model-predictive control (MPC) strategies for temperature-based compressor regulation. In 2023, several studies demonstrated that intelligent control algorithms significantly improve transient response and reduce temperature overshoot compared to conventional controllers (Ahmed et al., 2023; Zhao et al., 2023). Fuzzy logic controllers, in particular, handle nonlinearities in refrigeration systems effectively, while MPC offers predictive optimization by considering system constraints and future load variations.

Temperature-based control also enhances food preservation by maintaining a more uniform thermal environment. Experimental investigations show that VSD-controlled systems reduce temperature fluctuations by up to 60%, thereby improving product quality and shelf life

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(Ramos et al., 2023). The effectiveness of temperature-based control is further amplified when integrated with PV power, as compressor speed can be coordinated with solar power availability to optimize energy utilization.

4. Integration of Photovoltaic Power with VSD-Driven Refrigeration Systems

The integration of photovoltaic power into refrigeration systems involves combining solar panels, power conditioning units, energy storage, and control interfaces. PV panels generate DC electricity, which can either directly feed the DC-link of a VSD inverter or be converted through a DC–DC converter with MPPT control to maximize power extraction. In grid-connected configurations, excess solar energy can be exported to the grid, while in off-grid systems, battery storage ensures continuous operation during low irradiance periods.

Recent studies in 2023 highlight the advantages of direct PV-to-VSD coupling, which reduces conversion stages and improves overall efficiency (Moreno et al., 2023). Advanced MPPT algorithms such as incremental conductance and artificial intelligence-based methods have demonstrated faster tracking and higher efficiency under variable irradiance conditions (Chen et al., 2023). The coordination between PV output and compressor speed is critical; when solar power is abundant, the compressor operates at higher speeds to increase cooling capacity, while during low irradiance, speed is reduced to maintain essential cooling with minimal energy consumption.

Table 1 summarizes key PV integration configurations reported in recent literature.

Table 1. Configurations of PV-Powered VSD Refrigerator Systems (2023 Studies)

Configuration Type	Power Flow Characteristics	Key Advantages	Limitations
Direct PV–VSD coupling	PV DC directly feeds inverter	High efficiency, fewer components	Sensitive to irradiance fluctuations
PV with DC–DC MPPT	Regulated DC-link voltage	Stable operation, improved MPPT	Added converter losses
PV–Battery–VSD system	Energy storage support	Reliable off-grid operation	Higher cost and maintenance
Grid-connected hybrid	PV + grid backup	Maximum reliability	Grid dependency remains

The integration of PV systems with VSD-driven compressors thus offers a flexible and scalable solution adaptable to diverse operating conditions.

5. Performance Evaluation and Comparative Analysis

Performance evaluation of temperature-based VSD refrigerator systems powered by PV energy focuses on metrics such as energy consumption, coefficient of performance (COP), system reliability, economic viability, and environmental impact. Experimental and simulation studies published in 2023 consistently report substantial reductions in electricity consumption compared to conventional systems. Energy savings range from 25% to 45%, depending on climatic conditions, control strategy, and system configuration (Gupta et al., 2023; Torres et al., 2023).

The COP of refrigeration systems improves due to reduced cycling losses and optimized compressor operation. Studies indicate COP improvements of 15–30% under variable speed operation with temperature-based control. Additionally, PV-powered systems significantly lower carbon emissions by reducing reliance on fossil-fuel-based grid electricity. Life-cycle assessment studies in 2023 estimate emission reductions of up to 50% over the system lifetime (Hernandez et al., 2023).

Table 2 presents a comparative overview of conventional and PV-powered VSD refrigeration systems.

Table 2. Comparative Performance of Refrigerator Compressor Control Approaches

Parameter	Fixed-Speed Powered	Grid- Powered	VSD Powered	Grid- Powered	PV-Powered VSD
Energy efficiency	Low		Medium–High		High
Temperature stability	Poor		Good		Excellent
COP	Low		Improved		Highest
Carbon emissions	High		Moderate		Very low
Initial cost	Low		Medium		High
Long-term savings	Low		Moderate		High

Economic analyses show that although PV-powered VSD systems have higher initial costs, the payback period has reduced significantly due to declining PV prices and energy savings, with typical payback times reported between 4 and 7 years in 2023 studies.

6. Challenges, Future Trends, and Conclusions

Despite the demonstrated advantages of temperature-based VSD control using photovoltaic power, several challenges remain. System complexity increases due to the integration of power electronics, control algorithms, and renewable energy sources. Reliability concerns related to inverter components, battery degradation, and environmental exposure of PV panels must be addressed. Moreover, performance depends heavily on accurate temperature sensing and robust control tuning.

Future research trends identified in 2023 emphasize the adoption of artificial intelligence and machine learning techniques for adaptive control and fault detection. Smart refrigerators capable of communicating with the grid and participating in demand-response programs are gaining attention. The use of wide-bandgap semiconductor devices such as SiC and GaN in VSD inverters promises higher efficiency and compact designs. Additionally, hybrid renewable systems combining PV with wind or thermal storage are being explored to enhance reliability. In conclusion, temperature-based variable speed drive control of refrigerator compressor motors powered by photovoltaic energy represents a significant advancement toward sustainable refrigeration. The convergence of efficient motor technology, intelligent control strategies, and renewable energy integration offers substantial energy savings, improved performance, and reduced environmental impact. Continued research and technological innovation are expected to accelerate large-scale adoption, contributing meaningfully to global energy sustainability goals.

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