Iqra Journal of Engineering & Computing
Vol. 02, No. 1, (March 2026) 01 – 11
DOI 10.21621/ijec.20260101.01

Solar-Powered Variable Frequency Drive (VFD) Based Flour Grinding System

Muhammad Zain[1], Muhammad Ahmad[1], Muhammad Abdullah[1],
Hamza Ahmad Raza[1], Abdul Basit Taj[1], Misbah Sattar[2]

ABSTRACT

Pakistan's agricultural sector forms the backbone of its economy, with wheat being the staple crop, processed predominantly through small-scale flour grinders (Aata Chakkis). Alongside wheat, other grains such as maize (corn), barley, millet, rice, and chickpeas are also ground in these mills for daily consumption. However, these mills consume significant electricity, increasing operational costs and pressuring Pakistan's fragile power grid. With rising power costs and frequent outages, mill owners are adopting solar-powered solutions. This study explores how Variable Frequency Drives (VFDs) can optimize the efficiency of solar-powered flour grinders by providing grain-specific motor speed control, reducing electricity consumption, and maintaining smooth operation under fluctuating solar power. Different grains require different grinding speeds to ensure optimal flour texture, operational efficiency, and reduced wear on equipment. A cost comparison was conducted between conventional mills and VFD-controlled solar mills in terms of energy savings, performance, and payback periods. The study presents the practical implementation of a VFD system and its effectiveness in real-world applications.

Keywords: VFD, Induction Motor, Solar-Powered System, Flour Grinding Machine, Chakkis

Author's Affiliation:

Institution(s) Name:	[1] National University of Technology, Islamabad, [2] COMSATS University, Islamabad
Country:	Pakistan
Corresponding Author's Email:	[1]muhammadzain134f19@gmail.com

Published by ORIC, Iqra University, Main Campus, Karachi-Pakistan.

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1. Introduction

Pakistan's food security and rural livelihoods depend heavily on its agricultural output, with wheat serving as the most widely grown and consumed staple crop. At the beginning of the period from 1975 to 2020, Pakistan had achieved near self-sufficiency in wheat production [1]. In Pakistan, these grains are processed through two main types of setups: small-scale chakkis (flour grinders) and large-scale flour mills. While big mills handle large amounts of wheat for the formal market, it is the small chakkis that play a key role in daily life. These chakkis are found everywhere, from small villages to big cities. In cities, where people usually don't store grain at home, chakkis often buy wheat from the market and sell fresh flour. In this way, small-scale chakkis form a wide, informal network that quietly supports food needs across the country [2].

Traditionally, these Chakkis operated using hand-cranked stone grinders. Over time, however, they have evolved into electrically powered systems, often incorporating AC induction motors, reflecting the global shift from manual stone milling to modern mechanized techniques such as roller milling and automation [3]. However, this evolution came with its own set of challenges. Most modern small-scale flour grinders run continuously on grid electricity, which is often unreliable, especially in rural areas. Load shedding, power fluctuations, and rising electricity costs have made day-to-day operation both financially and operationally difficult. To deal with this, some people use diesel engines, but these alternatives bring high fuel costs and are harmful to the environment [4].

To overcome the challenges mentioned above, solar energy has become a good alternative. For an average of 10 hours per day, the solar radiation intensity in Pakistan, particularly in the southern regions of Punjab, Sindh, and Balochistan, ranges between 1.5 KW/m²/day and 2.75 kW/m²/day consistently throughout the year [5]. Many people are now trying to run flour mills using solar power. But there's a problem, solar panels produce DC power, while most flour grinders need AC power. This means an inverter is required, which then drives the induction motor. While simple inverters can convert DC from solar panels to AC for motor operation, they cannot adjust voltage and frequency dynamically based on fluctuating solar conditions [6].

In a solar-powered flour mill (chakki), using a Variable Frequency Drive (VFD) is more efficient and suitable than a simple inverter. A basic inverter only converts DC power from solar panels into fixed-frequency AC (typically 50 Hz), a VFD performs this conversion and allows precise control over the frequency and voltage supplied to the induction motor. This allows the system to regulate speed at the load demand, which reduces energy consumption at low demand levels and increases efficiency. Further, VFDs offer the capability of smooth start-up, torque control, and protection features that inverters do not have. Thus, in the case of a solar-powered chakki where solar energy optimization and motor performance are significant priorities, the VFD has several profound benefits over a conventional inverter [7].

Furthermore, while traditional flour mills typically run motors at constant speed regardless of grain type, different grains require different optimal grinding speeds to achieve desired flour texture, processing efficiency, and mechanical reliability. For example, maize requires higher grinding torque and speed than wheat, while softer grains like millet or barley perform better at lower speeds to avoid excessive heat buildup and nutrient loss.

However, despite the growing fascination with solar-powered grain mills, little research has explored the concept of integrating VFDs within such systems. Recently, a study designed a solar-powered maize milling machine to offer an efficient, off-grid machine for grain processing. This study highlights its efficiency, cost-effectiveness, and the potential reduction of dependency on fossil fuels for food security in rural areas [8]. Another recent study examined the feasibility of solar-powered grain mills, highlighting their potential contribution to energy efficiency and sustainability in rural areas. Their work suggests that renewable energy integration supports both operational cost reduction and environmental impact reduction [9]. However, their studies did not consider the role of VFDs in enhancing the efficiency of the motor's performance.

We have devised and tested a system of a VFD used with solar power for a flour mill. We started with designing and testing a system in MATLAB Simulink. Subsequently, we demonstrated how the use of a VFD can enhance the energy efficiency and cost-effectiveness of solar-powered flour grinders for long-term operation. The Block Diagram of the entire system is depicted in Figure.1.

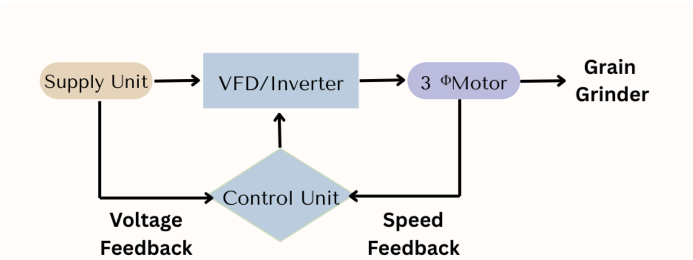

Figure.1 Block Diagram of the Overall System

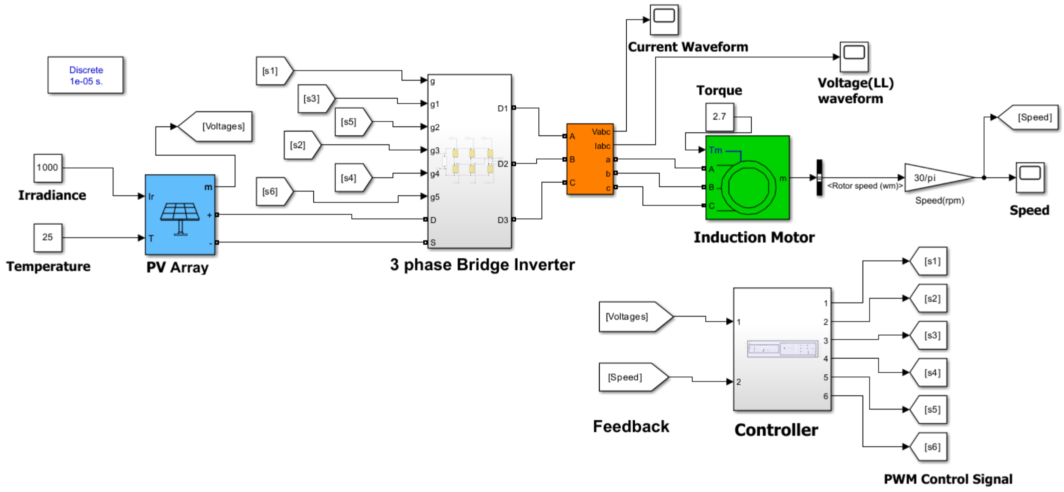

Figure.2 MATLAB Simulink Model of a Solar-Powered VFD System

2. Simulation and Experimental SetupSimulation

In MATLAB Simulink, we have designed and simulated a solar-powered Variable Frequency Drive (VFD) system. This system was used to simulate the operation of a domestic flour grinding unit powered by a 1 HP three-phase induction motor. In simulations, DC power from solar panels is fed to the VFD inverter, which converts it to variable 3-phase AC. The simulation is shown in Figure. 2.

A closed-loop control strategy was implemented using a PID controller to maintain stable motor operation under fluctuating solar conditions. This controller dynamically regulated both the voltage and frequency applied to the motor, ensuring the desired speed and torque were maintained. The control mechanism was based on the principle of maintaining a constant voltage-to-frequency (V/f) ratio, which is critical for preserving consistent torque output across varying speeds.

The synchronous speed of the motor, which determines the reference point for rotor speed control, is governed by the relation:

$$N_s = \frac{120\,f}{P} \qquad (1)$$

where N is the synchronous speed in RPM, f is the supply frequency in Hz, and P is the number of poles of the motor. This relationship highlights why a VFD is effective. By changing frequency, motor speed can be adjusted to match the optimal grinding requirement of each grain. This not only improves flour quality but also reduces unnecessary power consumption and wear on the grinder. VFDs exploit this relationship to provide dynamic speed control, making them highly suitable for applications like grain-specific grinding, where different materials require different operating speeds.

2.2. Experimental Setup

The system component required for the installation is described below:

2.2.1.Three-phase Motor

A three-phase induction motor to run the flour grinding machine is used because it is highly efficient, cost-effective, robust, and durable. Specifications of the motor are given in the table below.

Table 1: Motor Specifications

Parameters	Rating
Power	1 HP (0.75 KW)
Voltages	380 - 415 V
Current	2.14 – 1.96 A
Poles	4
Frequency	50 Hz
RPM	1420
Power Factor	0.8

2.2.2.Solar PV array Calculation

We used 540 W solar panels to run a 1 HP three-phase induction motor. Panel specifications are given below in the table.

Table 2: Panel Specifications

Parameters	Specification
Power Output	540W
Open Circuit Voltage (Voc)	49.65V
Short Circuit Current (Isc)	14A
Voltage at Maximum Power (Vmp)	41.8V
Current at Maximum Power (Imp)	13.01A
Number of Solar Cells	144 (12×6, 12×6)
Panel Type	Monocrystalline
Efficiency	21%

Our 3-phase motor typically operates at 380V-415V, which requires about 400 V DC from the solar panels to produce a 50 Hz AC voltage. As each panel provides 49.8 V, to achieve at least 400 V DC, 8 panels in series are used. Each panel offers 13.01 A (max), more than enough from a single string to run the motor. A parallel string of 8 panels is used, inclined from the ground at an angle of 45° is used.

2.2.3.Variable frequency drive (Inverter)

A three-phase VFD inverter operates a three-phase motor that converts DC output from solar panels to AC. As the motor power rating is 1 HP (0.75 kW), the VFD rating should be at least 2 times the motor power for better performance and handling of inrush currents. So, we designed a 2 kW VFD for our system for smooth and safe operation, shown in Figure. 3.

Figure.3 Three-Phase VFD Inverter

2.2.4.Flour Grinding Machine

An existing domestic flour grinding machine shown in Figure. 4 was upgraded by integrating our VFD-based speed control system to improve performance and energy efficiency for small-scale use. The system includes a 3-phase induction motor connected to the grinding unit through a belt and pulley mechanism, allowing smooth and controlled operation. When the VFD inverter is switched ON, DC power from solar panels is converted into three-phase AC, which powers the motor. This motor then drives the grinding mechanism to efficiently produce flour. The machine can grind approximately 20 kg of wheat in 1 hour and up to 100 kg in 5 hours, ideal for domestic or small-scale flour production.

Figure.4 Flour Grinding Machine

3. Results and Analysis

The experimental and simulation analysis demonstrated that the solar-powered VFD-based flour grinding system effectively operated a 1 HP three-phase induction motor without reliance on grid or battery support. A critical challenge was maintaining a stable torque-speed relationship amid variable solar output. This was addressed through a V/f (voltage-to-frequency) control strategy, allowing dynamic adjustment of motor speed, illustrated in Figure. 5.

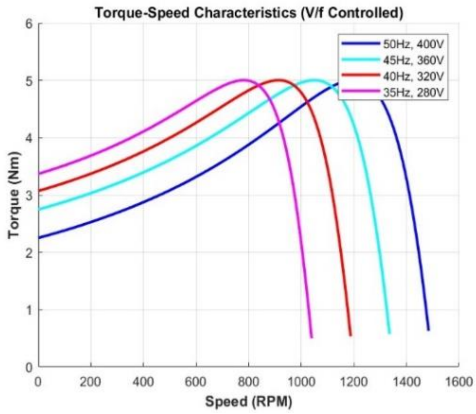

Figure.6 Torque Vs Speed Curves

One valuable finding was that different grains grind best at different speeds shown in Figure. 6. For instance, wheat achieved optimal grinding at 1400-1450 RPM (50 Hz), ensuring a balanced flour texture and energy efficiency. Maize (corn) required higher torque and was found to operate most effectively at 1500 RPM (55 Hz), resulting in improved grain crushing performance. Softer grains like barley and millet yielded better results at slower speeds of 1200-1300 RPM (42–46 Hz), which helped avoid overheating and preserve nutritional content. Rice is ground efficiently at 1350 RPM (48 Hz), minimizing grain breakage and maintaining flour consistency.

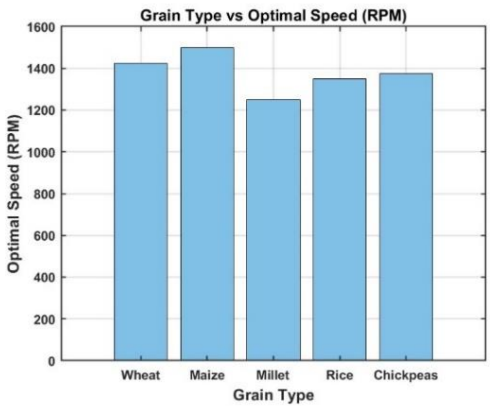

Figure.7 Grain type vs. optimal Speed

The torque-speed characteristics under different voltage and frequency combinations demonstrated effective torque retention across the desired speed ranges for all grain types. The VFD's Pulse Width Modulation (PWM) control allowed fine-tuned frequency adjustments in response to fluctuating solar conditions, ensuring consistent grinding performance. Using a VFD enabled precise adjustment of motor frequency to match ideal operating speeds for each grain, which not only improved flour quality but also reduced unnecessary power consumption and mechanical strain. For example, at lower frequencies while grinding millet, the motor consumed 20% less power compared to running constantly at 50 Hz. Similarly, increasing speed to 55 Hz for maize improved throughput by 15% without compromising torque or efficiency.

As the grinding speed decreases for grains like wheat, the power consumption also decreases, which is reflected in Figure. 7. This relationship confirms that adjusting motor speed based on grain type directly affects energy usage, enhancing overall system efficiency.

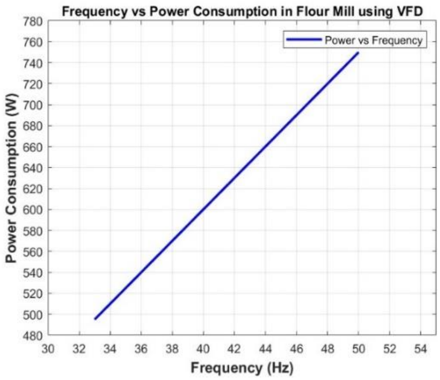

Figure.8 Frequency vs Power Consumption

To evaluate the cost-effectiveness of switching to a solar-powered VFD-based flour grinding system, a comparison was conducted against a conventional grid-powered model. The setup involves a 1 HP (0.75 kW) motor running for 5 hours daily with an 85% efficiency, resulting in an energy consumption of 4.4 kWh per day. Based on the current commercial electricity tariff of Rs. 80 per kWh, the estimated monthly operational cost reaches Rs. 10,560, as shown in Table 3.

Table 3: Monthly Electricity Consumption

Parameter	**Details**
Motor Rating	1 HP (0.75 kW)
Motor Efficiency	85%
Effective Power Consumption	0.88 kW
Daily Operating Hours	5 hours
Daily Energy Consumption	0.88 kW × 5 hrs = **4.4 kWh**
Electricity Tariff	Rs.80 per kWh
Daily Operating Cost	4.4 kWh × Rs.80 = **Rs.352**
Monthly Operating Cost (30 Days)	Rs.352 × 30 = **Rs.10,560**

On the other hand, the initial one-time cost of setting up the solar-based VFD system is as follows:

Table 4: Installation Cost

Component	Quantity	Unit Cost (Rs.)	Total Cost (Rs.)
540 W Solar Panels	10	16,000	160,000
VFD (2 kW)	1	25,000	25,000
Mounting & Installation	—	—	20,000
Total			205,000

Although the upfront cost of Rs. 205,000 seems significant, the monthly electricity savings of Rs. 10,560 make the payback period less than 20 months. After this period, the system effectively operates without energy cost, providing long-term savings and protection against electricity price hikes.

Moreover, ongoing maintenance costs remain minimal since the system uses no batteries and relies solely on direct solar power. The long lifespan of monocrystalline panels (typically 20-25 years) ensures sustainable, low-cost operation over the long term. This cost analysis highlights the economic feasibility of converting traditional grid-powered flour grinding units into solar-VFD-based systems, especially for rural or load-shedding-prone areas.

This adaptive, grain-specific speed control made possible by the VFD proved to be a key factor in enhancing the reliability, efficiency, and cost-effectiveness of the solar-powered flour grinder (atta chakki) system.

Using grid electricity at 4.4 kWh/day results in approx. 2.9 kg CO_2 emissions per day (based on 0.66 kg CO_2/kWh in Pakistan). Switching to solar avoids approx. 1,050 kg CO_2 annually, equivalent to planting approx. 50 trees.

4. Conclusion

This study successfully designed, simulated, and implemented a solar-powered flour grinding system incorporating a Variable Frequency Drive (VFD). The system effectively powered a 1 HP three-phase induction motor directly from solar panels using a voltage-to-frequency (V/f) control strategy, which ensured consistent torque output and efficient operation even under fluctuating solar conditions. One of the key achievements of the system was its ability to provide grain-specific speed control, optimizing performance for different grain types such as wheat, maize, barley, millet, and chickpeas.

The integration of VFD technology led to a significant reduction in power consumption and operational costs. The system operated smoothly without reliance on batteries or the national grid, making it a sustainable solution for off-grid regions. Furthermore, the economic analysis demonstrated a payback period of less than two year, after which the system delivers long-term financial savings.

Overall, the solar-powered VFD-based flour grinders (atta chakki) enhance energy efficiency, improve flour quality, and extend equipment lifespan. This makes it an ideal solution for rural and energy-challenged communities in Pakistan. Looking ahead, the system can be further improved by incorporating IoT-based monitoring, automation features, and Maximum Power Point Tracking (MPPT) to optimize solar power utilization in real-time.

5. Limitation

The experimental validation was performed over short operational durations. Long-term field testing in rural settings is planned as future work to assess durability and seasonal variations

Funding: No external funding was declared for this manuscript.

Conflict of Interest: The author declares no known conflict of interest.

Data Availability: Not applicable

Ethics Statement: This study does not involve human participants, patient records, animal subjects, or private organizational data. Any future case-study testing must be performed only on owned systems or systems with written authorization.

Author Contributions: The author is responsible for conceptualization, framework design, manuscript preparation, and final review.

Acknowledgment: The author acknowledges the role of all authors.

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