# Efficiency Optimization of Induction Motor Drive

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## ABSTRACT
Induction motors are extensively used in industrial and household appliances and consume more than 50% of the total generated electrical energy. The need for energy conservation is increasing the requirements for saving the electrical energy. It is therefore important to optimize the efficiency of electrical drive systems under light load condition. This paper proposes a control scheme based on search method taking advantage of the fact, that at a certain torque and speed (operating point) there is only one set of voltage & frequency that operates the motor at optimum efficiency. Utilizing equivalent loss model of induction motor, expressions of $V_{opt}$ , $F_{opt}$ are derived mathematically. Both simulation & experiment results indicates the efficiency performance with VVVF is superior to that of V/F operation in steady state and light load conditions. Future work is also suggested that if incase any frequent transients comes in load side, the optimization schemes can be abandoned & V/F operation should be implemented till the steady state comes.

## Keywords
Induction Motor Drive, Efficiency Optimization, VVVF, V/F

## 1. INTRODUCTION
Induction motors are the most used in industry since they are rugged, inexpensive, and are maintenance free. It is estimated that more than 50% of the world electric energy generated is consumed by electric machines. Improving efficiency in electric drives is important, mainly for economic saving and reduction of environmental pollution. Induction motors have a high efficiency at rated speed and torque. However, at light loads, motor efficiency decreases dramatically due to an imbalance between the copper and the core losses. Hence, energy saving can be achieved by proper selection of the flux level in the motor. The main induction motor losses are usually split into: stator copper losses, rotor copper losses, core (iron) losses, mechanical and stray losses. Induction motor drive can be controlled according to a number of performance functions, such as input power, speed, torque, air-gap flux, power factor, stator current, stator voltage, and overall efficiency. Basically, there are three strategies, which are used in efficiency optimization of induction motor drive: Simple state control, model based control, and search control. In this paper a control scheme based on search method taking advantage of the fact (Nola Theory), that at a certain torque and speed (operating point) there is only one set of voltage & frequency that operates the motor at optimum efficiency, is utilized. Also, with the help of loss model of induction motor, expressions of $V_{opt}$, $F_{opt}$ are derived mathematically (involving internal parameters of induction motor and their optimization process). Both simulation & experiment results indicates the efficiency performance with VVVF is superior to that of V/F operation in steady state. Also it is suggested that under transient situation, optimization schemes must be abandoned & V/F operation should be implemented.

## 2. VARIATION OF INDUCTION MOTOR EFFICIENCY
Recently, variable speed drives (VSDs) have been intensively applied in several VAC systems. A VSD is used to regulate the speed of a motor (fan or pump) to suit the demands placed upon it. It is clear that the same operating point can be obtained with different combinations of $V$ and $f$ (see Fig. 1). However, only one set will maximize the efficiency of the motor and it is possible to calculate this set for a given operating point.

In the next section, a typical procedure for calculating the unique set ($V$, $f$) that maximizes the IM efficiency for a given operating point ($T$, $w$) is discussed. As stated above, it is important to define the appropriate values of the applied voltage amplitude and frequency, for any operating point, which maximize the efficiency of the motor.

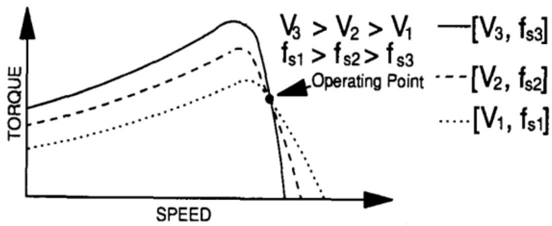



Fig 1. Steady – state torque – speed char.

## 3. DETERMINATION OF OPTIMAL VOLTAGE AND FREQUENCY
In this section, mathematical derivation will be given to obtain the expressions for the optimal efficiency operation of induction motor under specified speed and torque. Starting from the induction motor equivalent circuit (Fig. 2),

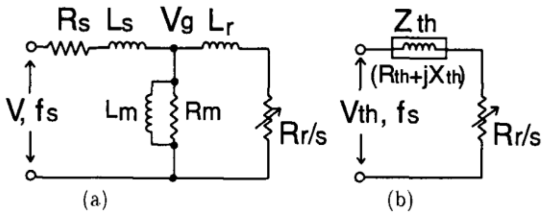



Fig. 2. (a) The equivalent circuit of induction motor

(b) The Thevenin equivalent voltage $V_{th}$ and equivalent impedance $Z_{th}$ circuit

Power input

$P_{in} = VI\cos\Theta = V^2(R_r/s+R_{th})/[(R_r/s+R_{th})^2+X^2_{th}]$ (1)

And the electromagnetic torque

$T_e = P_{out}/\omega_r = [i^2R_r/s]/[\ \omega_s(1-s)]$

## 4. DESIGN OF OPTIMAL CONTROLLER

To design the efficiency optimization controller based on search method, a matrix, as shown in **Table 1** consisting of loads, frequencies and stator voltage values (optimal), which maximize the efficiency, is constructed using the mathematics discussed in the previous section.

$=[V^2R_r/s]/\{\omega_s(1-s)[(R_r/s+R_{th})^2+X^2_{th}]\}$ (2)

Taking $\lambda$ be the lagrange multiplier and defining as,

$L = [V^2R_r/s]/\{\ \omega_s(1-s)[(R_r/s+R_{th})^2+X^2_{th}]\}+ \lambda\{([\ V^2R_r/s]/\{\omega_s(1-s)[(R_r/s+R_{th})^2+X^2_{th}]\})-T\}$ (3)

Taking the optimization procedures

$\partial L/\partial V = 0$ and $\partial L/\partial \omega_s = 0$ (4)

and the adjoint equation

$\partial L/\partial \lambda = [V^2(R_r/s)/[\omega_s(1-s)\{(R_{th} + R_r/s)^2 + X_{th}^2\}]] - T = 0$ (5)

After some manipulations [3], we have

$s = 1- (\ R_r/R_{th})$ (6)

This yields the required input frequency and voltage for optimal efficiency

$\omega_s = \omega_r\ (\ R_r\ /\ R_{th})$ (7)

$V_{opt} = [(Tw_s\{(R_r/s+R_{th})^2+X_{th}^2\}/(\ R_r/s+R_{th})]^{1/2}$ (8)

It is seen that for optimal efficiency operation of induction motor, the required input frequency depends on speed only, while the input voltage is proportional to the square root of torque and frequency. For under load condition the optimized efficiency is obtained when the motor is supplied with voltage as shown above and with above frequency

LOAD TORQUE (N-m)

FREQUENCY

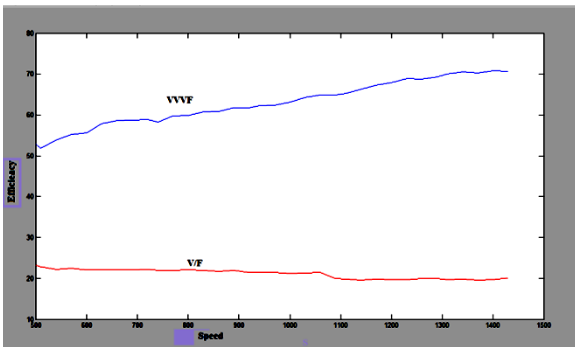
| Volts | 1 | 1.25 | 1.5 | 1.75 | 2 | 2.25 | 2.5 | 2.7 | 3 |
|---|---|---|---|---|---|---|---|---|---|
| 17 | 83 | 93 | 102 | 110 | 117 | 124 | 131 | 138 | 144 |
| 18 | 84 | 95 | 104 | 112 | 120 | 127 | 134 | 140 | 147 |
| 19 | 87 | 97 | 106 | 115 | 123 | 131 | 138 | 144 | 151 |
| 20 | 89 | 99 | 108 | 117 | 125 | 133 | 141 | 147 | 154 |
| 21 | 91 | 102 | 111 | 120 | 129 | 136 | 144 | 151 | 158 |
| 22 | 93 | 104 | 114 | 123 | 132 | 140 | 147 | 155 | 161 |
| 23 | 95 | 107 | 117 | 126 | 135 | 143 | 151 | 158 | 165 |
| 24 | 98 | 109 | 119 | 129 | 138 | 146 | 154 | 162 | 169 |
| 25 | 100 | 111 | 122 | 132 | 141 | 149 | 158 | 165 | 173 |
| 26 | 101 | 113 | 124 | 134 | 143 | 151 | 160 | 168 | 175 |
| 27 | 103 | 115 | 126 | 136 | 146 | 155 | 163 | 171 | 179 |
| 28 | 105 | 117 | 129 | 139 | 148 | 158 | 166 | 174 | 182 |
| 29 | 107 | 119 | 131 | 141 | 151 | 160 | 169 | 177 | 185 |
| 30 | 109 | 122 | 133 | 144 | 154 | 163 | 172 | 181 | 189 |
| 31 | 111 | 124 | 136 | 147 | 157 | 166 | 175 | 184 | 192 |
| 32 | 112 | 126 | 138 | 149 | 159 | 169 | 178 | 187 | 195 |
| 33 | 114 | 127 | 139 | 151 | 161 | 171 | 180 | 189 | 197 |
| 34 | 116 | 129 | 142 | 153 | 164 | 174 | 183 | 192 | 200 |
| 35 | 117 | 131 | 144 | 155 | 166 | 176 | 186 | 195 | 204 |
| 36 | 119 | 133 | 146 | 158 | 169 | 179 | 189 | 198 | 207 |
| 37 | 121 | 135 | 148 | 160 | 171 | 181 | 191 | 201 | 210 |
| 38 | 123 | 137 | 150 | 162 | 173 | 184 | 194 | 203 | 213 |
| 39 | 124 | 138 | 151 | 164 | 175 | 186 | 196 | 205 | 214 |
| 40 | 125 | 140 | 154 | 166 | 177 | 188 | 198 | 208 | 217 |
| 41 | 127 | 142 | 156 | 168 | 180 | 191 | 201 | 211 | 220 |
| 42 | 129 | 144 | 158 | 170 | 182 | 193 | 204 | 213 | 223 |
| 43 | 130 | 146 | 159 | 172 | 184 | 195 | 206 | 216 | 226 |
| 44 | 132 | 147 | 161 | 174 | 186 | 198 | 209 | 219 | 229 |
| 45 | 133 | 149 | 163 | 176 | 189 | 200 | 211 | 221 | 231 |
| 46 | 134 | 150 | 165 | 178 | 190 | 202 | 213 | 223 | 233 |
| 47 | 136 | 152 | 167 | 180 | 192 | 204 | 215 | 226 | 236 |
| 48 | 137 | 154 | 168 | 182 | 194 | 206 | 217 | 228 | 238 |
| 49 | 139 | 155 | 170 | 184 | 197 | 209 | 220 | 231 | 241 |
| 50 | 140 | 157 | 172 | 186 | 199 | 211S | 222 | 233 | 243 |

**TABLE 1**

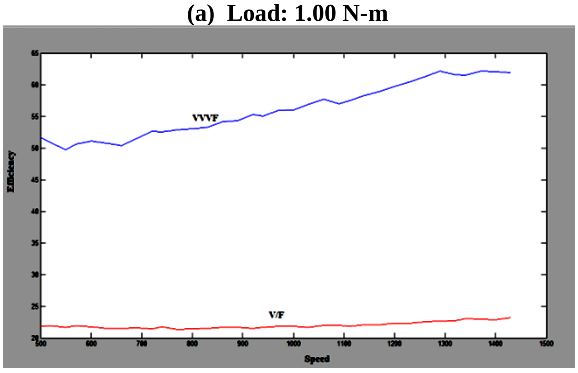
The matrix shown in **Table 1** will serve as the main part of the proposed efficiency optimization controller. The output of the controller will be the modulation index m, which correspondences the optimal value of voltage maximizing the efficiency under certain operation condition.

## 5. RESULTS AND DISCUSSION

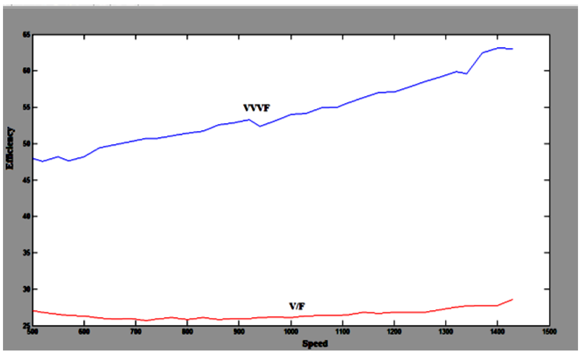
Comparison of Efficiency at different speed for same amount of load is shown here in **fig. 3.**



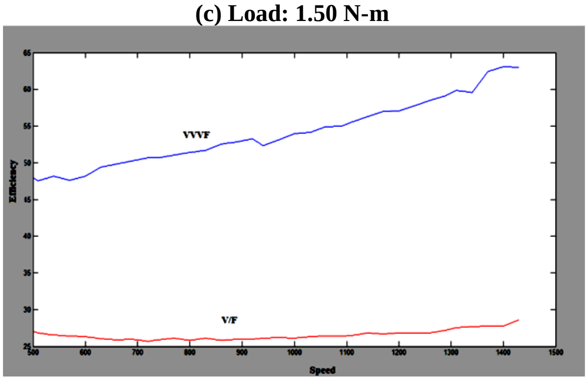

**(a) Load: 1.00 N-m**



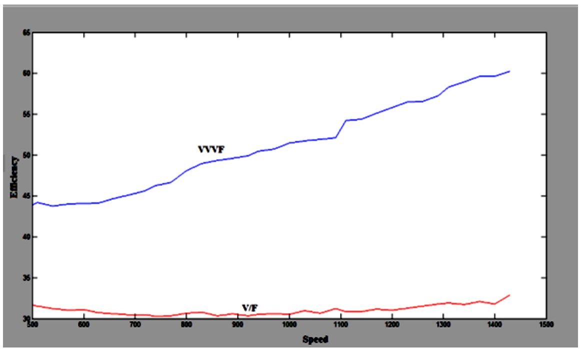

**(b) Load: 1.25 N-m**



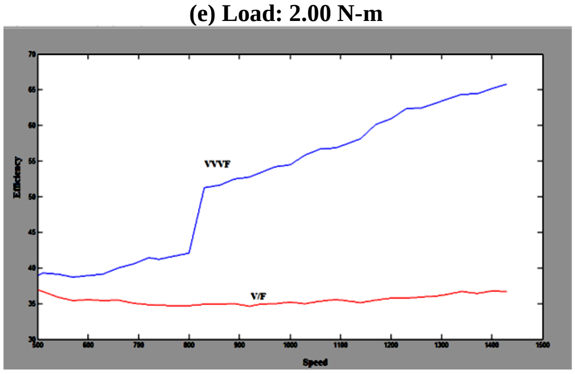

**(c) Load: 1.50 N-m**



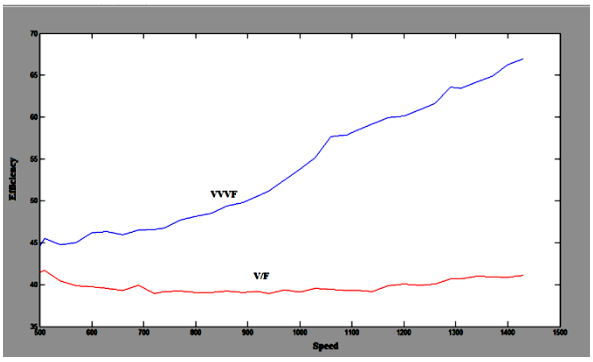

**(d) Load: 1.75 N-m**



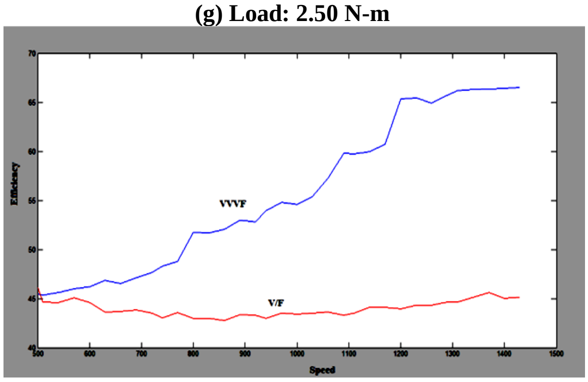

**(e) Load: 2.00 N-m**




**(f) Load: 2.25 N-m**




**(g) Load: 2.50 N-m**




**(h) Load: 2.75 N-m**

**Fig. 3. Efficiency at Different Speed and Load**

## 6. CONCLUDING REMARKS

In this paper, first it is verified that the VVVF method is superior than V/f method under light load condition and steady state in terms of energy saving, in general 15 – 20% improvement is seen on 1 HP motor. So it can be suggested to replace V/f with VVVF controller particularly for HVAC applications where speed control is not very important criteria.

## 7. FUTURE WORK

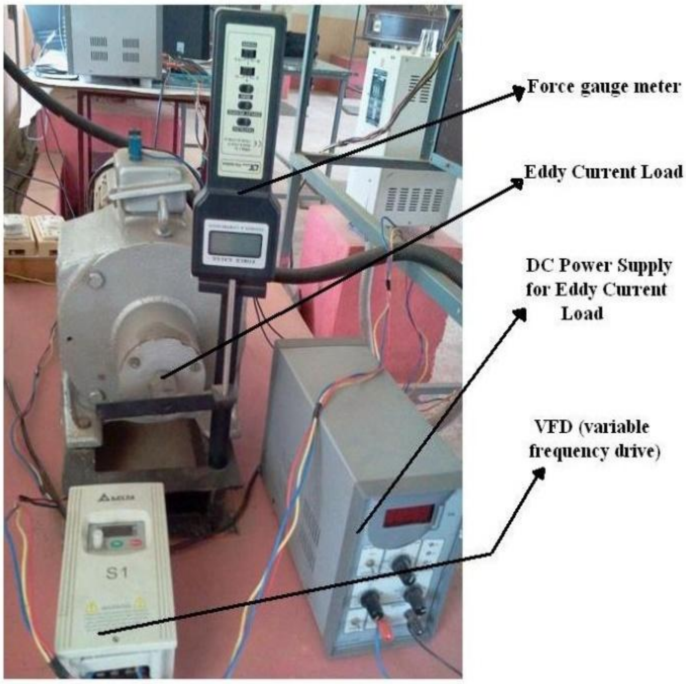
In the next step an attempt will be made to implement this theory to such a system where speed regulation is important. For that purpose an ANN will be trained offline and then the online implementation will be done with the hardware facility available as well as one another controller will be also included to monitor the load transients and accordingly select or abandon V/f and VVVF control scheme based on real – time observations and estimations.

## 8. APPENDIX

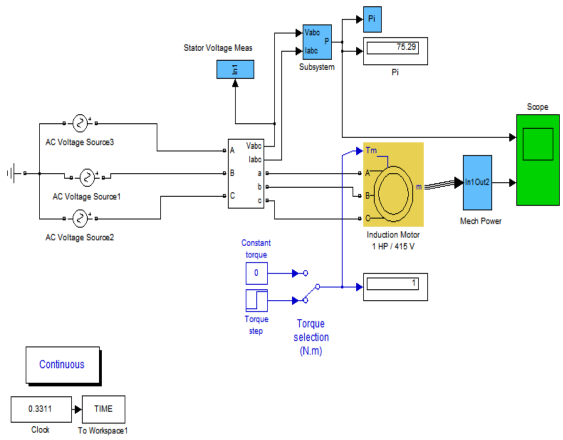
**Motor Specifications**

| | | |
|---|---|---|
| Number of pole | : | 4 |
| Phase | : | 3 |
| Rated Power | : | 0.75 KW |
| Rated Voltage | : | 415 V (Star) |
| Rated Current | : | 1.8 A |
| Supply frequency | : | 50 Hz |
| Rated Speed | : | 1395 rpm |
| Power Factor | : | 0.81 |
| Weight | : | 14 G |

## 9. Practical Setup




## 10. Matlab Simulation

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