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Higher Eddy current losses occur at the harmonic frequencies as the losses are proportional to the square of the frequency.

Relationship between Eddy current losses and frequency:

$$P_{EC} = P_{EF} \times \sum_{h=1}^{h_{max}} I_h^2 h^2 \text{ ----- (1.1)}$$

Where, P_{EC} = total Eddy current losses

P_{EF} = eddy current losses at full load at fundamental frequency

I_h = Root-Mean-Square (RMS) current (per unit) harmonic, h

h = harmonic number

Increased copper losses are due to the increased RMS value of current caused by the additional harmonic currents that pass through the winding of resistance, R.

$$P_{CU} = I_{RMS} \times R \text{ ----- (1.2)}$$

$$I_{RMS} = (\sum_{n=1}^{n=N} (I_n)^2)^{\frac{1}{2}} \text{ ----- (1.3)}$$

Where, P_{CU} = copper losses

R = winding resistance

I_{RMS} = combined RMS value of the fundamental current and harmonic currents

I_n = magnitude of nth harmonic

Furthermore, harmonics are undesired when it is required that generators and motors work smoothly (reduced noise and oscillations). Harmonics are produced in pairs composed of positive and negative sequences. Positive sequence harmonics, for example, 7th harmonic rotates in the same direction as the fundamental frequency and induces a positively rotating 6th harmonic in the rotor. Negative sequence harmonics, for example, 5th harmonic rotates against the direction of the rotor and produces a negatively rotating 6th harmonic in the rotor. These harmonic pairs (positively and negatively rotating 6th harmonic), for the 5th and 7th harmonic, create torque pulsations at six times the fundamental frequency resulting in undesired mechanical oscillations on the generator or the motor shaft. Consequently, this can damage the shaft.

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1.5 Outline of chapters

The dissertation consists of 6 chapters.

Chapter 1 introduces the need for reactive power compensation to make a power system become more reliable and 'healthy'. Also, the effects of harmonics on the different parts of the transmission system due non-linear loads were discussed.

Chapter 2 involves the different methods of reactive power compensation and gives an idea of how existing static and dynamic are used in power systems.

The proposed solution based on AC choppers and its principle of operation is clearly discussed in chapter 3 and its ability to provide reactive power compensation will also be explored.

Design of a power system incorporating the proposed SVC based on high frequency pulse-width modulation which is used to compensate or rather regulate the voltage across a load is carried out in chapter 4.

The system is the implemented on MATLAB/SIMULINK (2008) software and the simulation examining the performance of the compensation is presented in chapter 5.

Conclusions drawn from the proposed concept are presented in Chapter 6 as well as future works are also discussed.

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Chapter 2: Techniques of reactive power compensation and existing resources

2.1 Introduction

Generally, a complex power system is composed of numerous sources and loads whereby the flow of reactive and active power is determined by voltages and impedances and particular points in the network. However, there is no such control over the transmission loading which leads to a lack of controllability over the reactive and active power flow in the grid, thereby making the latter less reliable. Thus, there is a need to exercise control over parameters such as impedances, voltages, currents and phase angles to improve the controllability and reliability of the ac network. This chapter presents methods that are used to compensate for reactive power and some concepts on static and dynamic resources that are used in the compensation of reactive power.

2.2 Techniques of reactive power compensation

2.2.1 Transmission of power in an AC network

An electric utility system can be viewed as an inductive transmission line with series reactance, X connecting two sources, i and j . The sending end voltage is denoted by V_s and the receiving end voltage by V_r . The transmission line is considered to be lossless so that the resistance of the line is 0Ω [7]. V_s is considered as the reference phasor so that it leads V_r by an angle of δ [1].

$$\delta = \angle V_s - \angle V_r \quad (2.1)$$

The two machine system is as shown in figure 2.1.

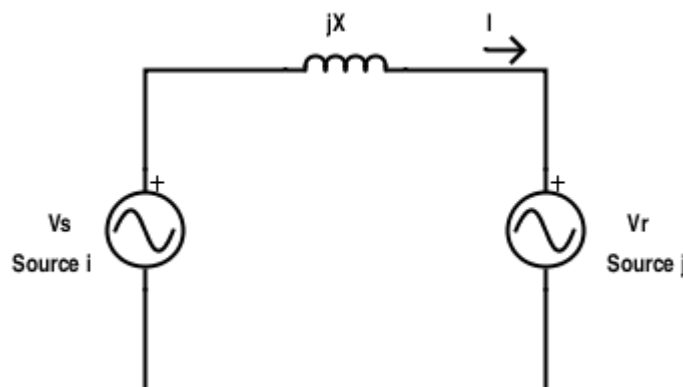


Figure 2. 1: Transmission line connecting two sources.

Let S_{ij} and S_{ji} be the line powers that flow from source i to source j and source j to source i respectively.

The line current, I is given by:

in series with the line impedance such that the impedance of the PST cancels the impedance of the transmission line to eliminate the problem of overloading. The principle of operation of the PST is to inject a voltage such that it is maintained fixed at $\pm 90^\circ$ with respect to the line voltage. The resulting voltage has a phase shift which is dependent of the introduced compensator voltage. PSTs are used especially in the control of real power flow along parallel paths which is dependent on system's transmission line impedance. By controlling the real power flow along the line, the reactive power consumed or produced by the line also becomes controllable. The disadvantage of PST is that they have a slow response time because these devices make use of mechanical taps to inject the required voltage and thus they are preferred to be operated under steady-state system conditions. Also, PSTs cannot provide dynamic control over reactive power as they are based on load forecasting techniques [11], [12].

2.3.1.3 Transformer tap changers

It is often desired that the voltage on the primary side and secondary side of a transformer to be controlled. This can be achieved by equipping the power transformer with tap changers which can control the amount and direction of flow of reactive power through the transformer depending on the settings of the tap. This configuration is called Load Tap Changer (LTC) because of its ability to switch positions with load current flowing. The tap changers, located on the primary or secondary side of the transformer windings, control the voltage by forcing voltage on one side of the transformer to go up which in turn, results in the lowering of the voltage on the other side [12]. Tap changers can be categorised into two types – off-load tap changers and on-load tap changers (OLTC). Off-load tap changers are used to do adjustments when the transformer is de-energised and are preferred to be located on the low voltage side of the transformer and OLTCs on the contrary are usually located on the high voltage of the transformer because of their current-commutation capacity and are operated under load. Tap changers are categorized into mechanical, thyristor-assisted and solid state tap changers. The mechanical tap changer consists of insulators and contacts which when subjected to high currents, degrade over time and thus require regular maintenance. Thyristor-assisted and solid state tap changers eliminate the problem of constant maintenance because they make use of thyristors to switch current in and out of the system but the use of thyristors cause significant conduction losses. Also, these semiconductors are quite expensive and their configuration is quite complex when control strategies are analysed [9]. Load tap changers have a slow response time as

Therefore,

$$V_L(t) = F(t) \times V_{in}(t) = DV_m \sin wt + \sum_{i=1}^{\infty} D_i V_m \sin[wt(ix + 1) - i\theta] - \sum_{i=1}^{\infty} D_i V_m \sin[wt(ix - 1) - i\theta] \text{----- (3.6)}$$

$$I_L(t) = \frac{V_L(t)}{X_L(t)} = \frac{DV_m}{wL} \sin(wt - 90^\circ) + \sum_{i=1}^{\infty} \frac{D_i V_m}{(ix+1)wL} \sin[(ix + 1)wt - i\theta - 90^\circ] - \sum_{i=1}^{\infty} \frac{D_i V_m}{(ix-1)wL} \sin[(ix - 1)wt - i\theta - 90^\circ] \text{----- (3.7)}$$

Where, $X_L(t)$ is the reactance of the inductor of inductance L as a function of the switching function.

The inductor current is chopped by the switch $S1$ so that the input current, $I_{in}(t)$ is given by:

$$I_{in}(t) = I_L(t) \times F(t) \text{----- (3.8)}$$

For the sake of simplicity, the fundamental component of the inductor current and that of the switching function, $F(t)$ is considered. Thus, the fundamental input current, $I_{in1}(t)$, free from harmonics, is given by:

$$I_{in}(t) = D \times \frac{DV_m}{wL} \sin(wt - 90^\circ) = \frac{D^2 V_m}{wL} \sin(wt - 90^\circ) \text{----- (3.9)}$$

From equation (3.9), the fundamental impedance, Z_{in1} as seen from the input side is given by:

$$Z_{in1} = \frac{V_{in}(t)}{I_{in}(t)} = \frac{V_m \sin wt}{\frac{D^2 V_m}{wL} \sin(wt - 90^\circ)} = \frac{wL}{D^2} \text{----- (3.10)}$$

Thus, from equation (3.10), it can be concluded that impedance of the switched-inductor branch can be varied by changing the switching duty cycle, D . Given that the root-mean square (RMS) value of the applied voltage, $V_{in}(t)$ is V_{RMS} , the reactive power, Q_L (which is free from harmonics) absorbed by the switched-inductor branch is then given by:

$$Q_L = \frac{V_{RMS}^2}{Z_{in1}} = \frac{V_{RMS}^2}{wL} D^2 \text{----- (3.7)}$$

Thus, reactive power control can be achieved by adjusting the duty cycle.

The proposed SVC also needs to be able to inject leading reactive power in the system. This is achieved by placing a capacitor in parallel with the switched-inductor branch as shown in figure 3.6.

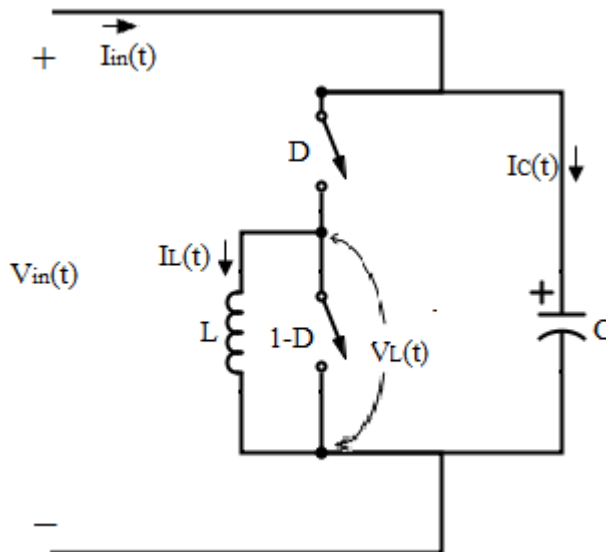


Figure 3. 6: Capacitor in parallel with the switched-inductor branch

Given that the reactance of the capacitor is X_c , the leading reactive power, Q_c that is supplied by the capacitor is given by:

$$Q_c = \frac{V_{RMS}^2}{X_c} \quad (3.8)$$

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3.4 Operation of the AC Chopper based SVC

For the design of the proposed SVC, MOSFETs are used to model the switches as shown in figure 3.7.

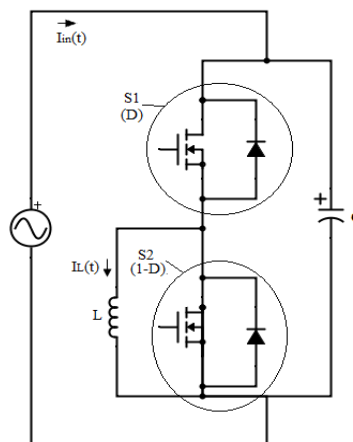


Figure 3. 7: Implementing the S1 and S2 using power MOSFETs

$$\text{Reactive power demand of load, } Q_{1\phi} = P_{1\phi} \times \tan(\cos^{-1} 0.85) = 6.32\text{MVar} \text{ ---- (4.11)}$$

Load resistance, R and inductance, L are given by:

$$P_{1\phi} = I_p^2 R \Leftrightarrow R = 10.2\Omega \text{ ---- (4.12)}$$

$$Q_{1\phi} = I_p^2 X \Leftrightarrow X = 2\pi f L = 6.32\Omega \Leftrightarrow L = 20.12\text{mH} \text{ ---- (4.13)}$$

$$\text{Impedance of the transmission line, } X_L = 20 \times 0.2 = 4\Omega \text{ ---- (4.14)}$$

From equation (4.14), the inductance, L_s of the transmission line is given by:

$$X_L = 2 \times \pi \times 50 \times L_s = 4\Omega \Leftrightarrow L_s = 12.73\text{mH} \text{ ---- (4.15)}$$

Figure 4.2 shows the single-phase equivalent circuit of the power system.

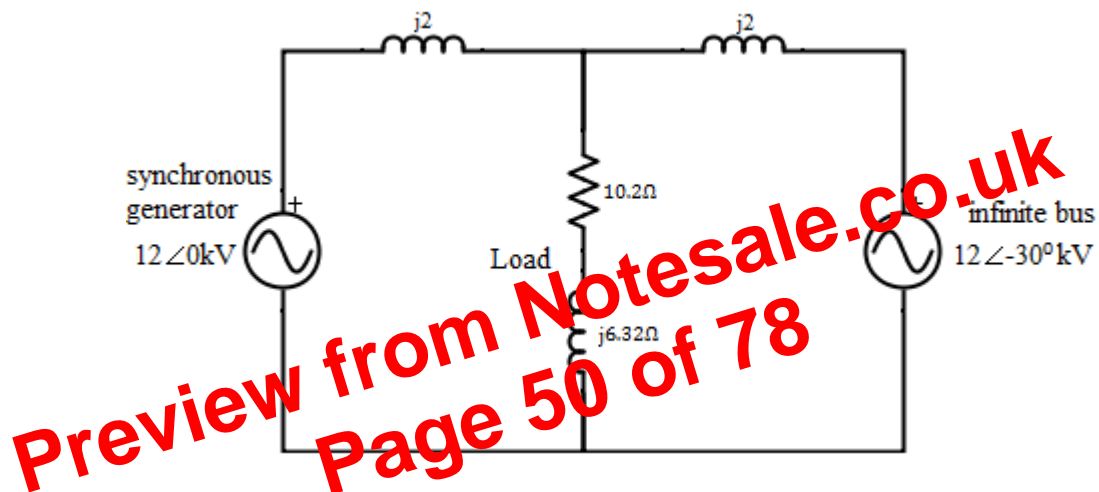


Figure 4. 2: Single phase model of the power system

4.4 Sizing of the capacitor and the inductor of the VAr compensator

The capacitor was chosen so that it is able to supply reactive power rated at 90MVar and the inductor was chosen so that it can absorb 100MVar reactive power.

$$\text{Capacitance of Capacitor, } C = \frac{Q_c}{V_p^2 \times 2\pi f} = \frac{90 \times 10^6}{12000^2 \times 2\pi \times 50} = 1990\mu\text{F}$$

$$\text{Inductance of Reactor, } L = \frac{V_p^2}{Q_r \times 2\pi f} = \frac{12000^2}{100 \times 10^6 \times 2\pi \times 50} = 4.56\text{mH}$$

4.5 Design of the closed loop system

The block diagram for the proposed closed loop system is shown in figure 4.3

The purposed of the closed loop system is to maintain the desired voltage across the load. This is achieved by measuring the root-mean-square (RMS) value of the load

voltage and is compared to another RMS value which is called the reference RMS value. The difference between the measured RMS value and the reference RMS value, that is, the error signal is attenuated first by a factor of 0.001 to reduce the high level of voltage (in the range of kV) and then is fed into a feedback controller, that is, the Proportional-Integral controller (PI-controller) which attempts to minimise the error signal to its smallest possible value. The output of the PI controller is modulated with a saw-tooth waveform, also referred to as the carrier signal. This is done by comparing the output of the PI controller with the saw-tooth waveform using a comparator such that when the output signal of the PI controller is less than or equal to the signal of the saw-tooth, the output of the comparator is 1. As a result, pulses are generated which are used to find the duty ratio of the PWM output and from which the duty cycle of the switch of the AC chopper can be found. The frequency of the saw-tooth signal is the switching frequency, F_s of the switch itself.

The switching frequency, F_s of the switch in the design of the AC chopper is chosen to be 1 kHz. Thus, the time period of the saw-tooth waveform is calculated as: $T_s = \frac{1}{F_s} = 0.001s$. The waveforms of the carrier signal, reference signal and the pulse-width modulated output are shown in figure 4.3.

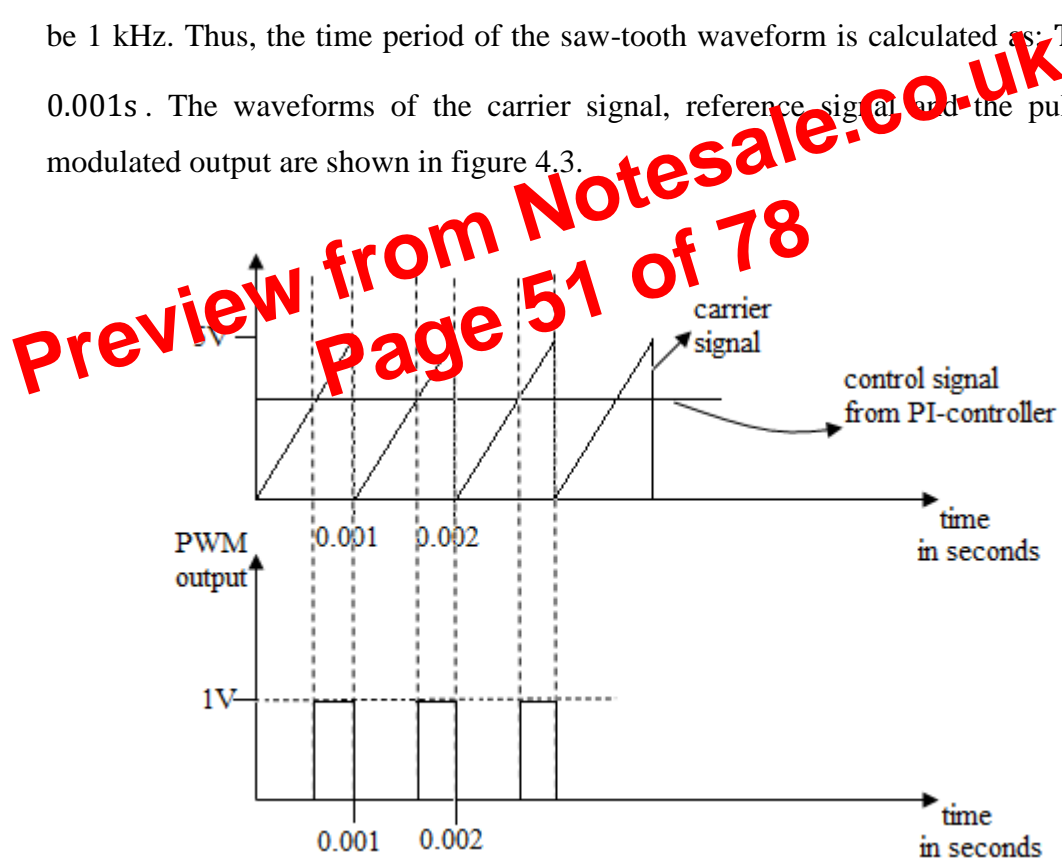


Figure 4. 3: Pulse Width Modulated output

Figure 5.9 shows the frequency spectrum of the load voltage for the effective load impedance, Z_L .

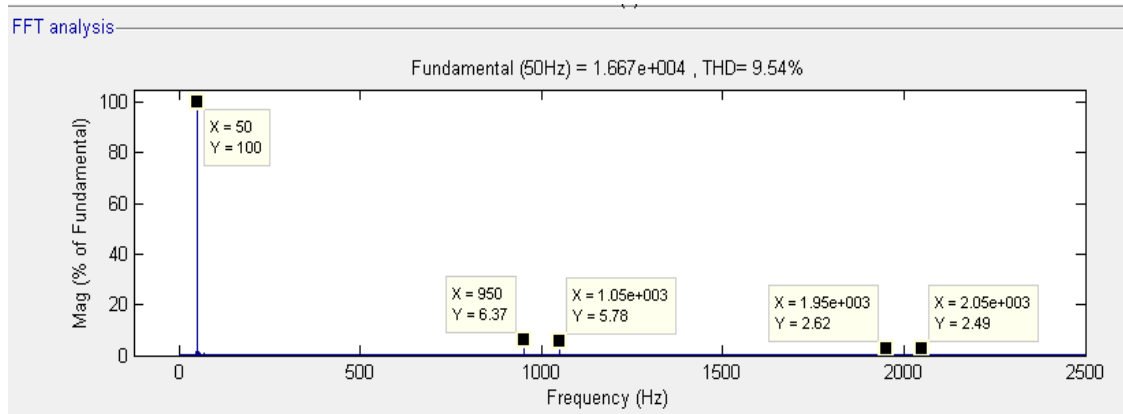


Figure 5. 9: frequency spectrum of load voltage when no load disturbance is applied.

Figure 5.10 shows the frequency spectrum of the load voltage for the effective load impedance, $0.9Z_L$.

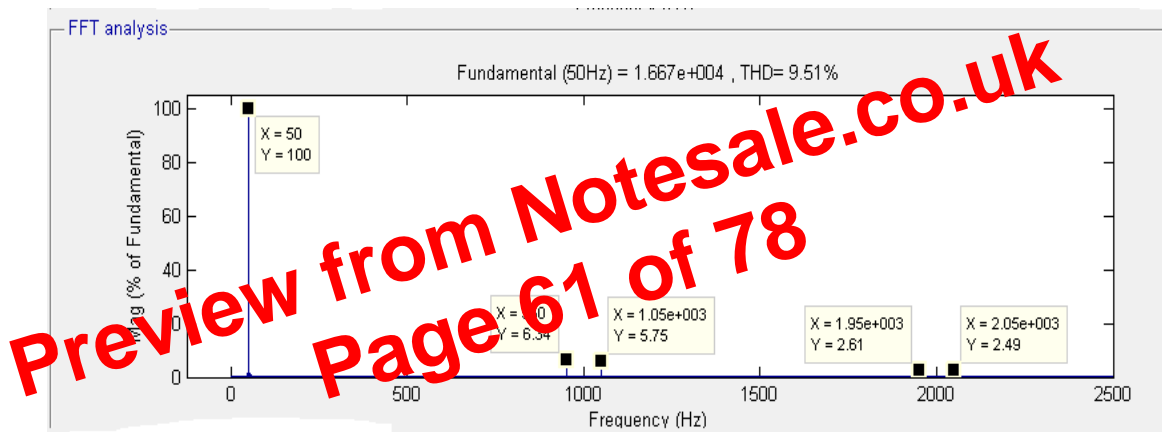


Figure 5. 10: frequency spectrum of load voltage when the load disturbance = $0.9Z_L$.

Figure 5.11 shows the frequency spectrum of the load voltage for the effective load impedance, $0.5Z_L$.

6.1 Conclusions

The aim of the dissertation was to study a Static VAR Compensator which is based on principle of operation of the AC-chopper, the switching frequency of which was chosen to be much higher than the fundamental frequency so that the low order harmonics are situated at high frequencies and thus, filtering of the undesired components of load voltage and current can be achieved more easily. The proposed SVC consisted of a switched inductor which was connected in parallel with a capacitor. The capacitor was fixed and thus, the reactive power that it supplied was also fixed. By employing a proper automatic control method, the duty cycle was varied in such a way that the appropriate switching pulses for the operation of switches were generated. Thus, the inductor absorbs the excess reactive power that was supplied by the capacitor. Automatic voltage compensation was carried out by using a PI-controller which minimised the difference between the measured load voltage and the desired load voltage.

The power system incorporating the SVC was designed and implemented on MATLAB/Simulink. The simulation results were deemed satisfactory, especially when the main objective to show that the harmonics produced were pushed to higher frequencies was expected. The frequency spectrum of the load voltage was analysed where it was shown clearly that the harmonics were produced at $(Mf_s \pm f_1)$ Hz. The THD in the load voltage decreased when the load disturbance became smaller. Also, the load voltage across the load was regulated so that the fluctuations produced were less than $\pm 5\%$. This enabled the compensator to provide the load with the power that it demands. The waveforms for the inductor current and voltage that were recorded matched those that were expected in theory. Hence, it can be concluded that the AC chopper-based SVC operation was satisfactory.

6.2 Recommendations for future works

Improvements for the proposed SVC:

- 1) Comparing it to the thyristor-based SVC so that their respective frequency spectrum could be analysed and hence, the THD could be compared. Also, the size of the filter that is required for both of these SVCs could have been designed to compare the cost benefits.
- 2) The hardware implementation of the system could be carried out later to test the efficacy of the compensator. Also, the hardware results could be compared to

Appendix E: Closed loop power system circuit

