Power Meter Front End Design:
The Delta Connection

Atmel’s AT73C500 + AT73C501-based meter chipset measures power and energy in three-phase systems or, alternatively, the chipset can be set to operate in a mode where it measures three separate, single-phase connections. In normal modes of operation, the chipset measures Y-connected three-phase, four-wire environments, but there is no dedicated operating mode for Delta-connected three-phase, three-wire systems. This application note describes how to implement the chipset in three-phase, three-wire environments.

Three-Phase Basics
To understand the measurement method, it is important to outline some of the following basic concepts.

Terminology
Voltages (and currents) in a three-phase system are referred to as either phase voltages (currents) or main voltages (currents), depending on the point of reference.

- **A Phase Voltage** \((U_{P1}, U_{P2} \text{ and } U_{P3})\) is always referenced to the neutral wire. In systems where there is no physical neutral wire, the phase voltages are referenced to a virtual neutral.

Note: 1. Also called neutral voltage. This should not be confused with the ground neutral that is at zero potential.

- **The Main Voltage** \((U_1, U_2 \text{ and } U_3)\) is defined as the voltage between two of the phase conductors.

- **A Phase Current** \((I_{P1}, I_{P2} \text{ and } I_{P3})\) is the current flowing through the load impedance. Depending on the type of connection, this current is not necessarily directly measurable from the meter connection points, but must be derived from the vector sum of other currents.

- **The Main Current** \((I_1, I_2 \text{ and } I_3)\) is defined as the current that flows through the phase conductor. Depending on the type of connection, this current is not necessarily the same that flows through the load.

The Star Connection
A typical three-phase, four-wire service with a grounded neutral is illustrated in Figure 1. The system shown is commonly referred to as a \(YN\)-configuration, with the subscript denoting there is a neutral wire present. The wiring method is sometimes also referred to as Star connection.

In Figure 1, the circuit on the left illustrates the power generator and the circuit on the right the load. In this type of connection, the energy meter would interface to measure the phase voltages \((U_{P1}, U_{P2} \text{ and } U_{P3})\) and phase currents \((I_{P1}, I_{P2} \text{ and } I_{P3})\).

In a balanced (all loads are equal) Star connection, the neutral line carries no current and the main current is equal to the phase current. The main voltage is related to the phase voltage as follows:

\[ U = \sqrt{3} \times U_p \]
The Delta Connection

The number of wires may be reduced from four to three, if the load is wired in Delta-configuration. It is noted that the generator does not necessarily have to be wired in Delta-configuration, it can also be Star-connected. An example of both the generator and the load-connected in Delta-configuration is illustrated in Figure 2.

The connection in Figure 2 contains no neutral wire and the inherent voltage marking therefore refers to main voltages (measured between phase conductors). When recalculating main voltages to phase voltages, the voltages are referenced to a virtual neutral wire.

It is noted, that in a balanced Delta connection, the relationship between phase current and main current is:

\[ I = \sqrt{3} \times I_p \]
Front End Connections
The schematic diagram on page 7 shows a method for connecting the A/D converter to three-wire service. The example Delta connection is rated for a 230/400V system, but may easily be adapted to any other rating.

The Voltage Front End
The two transformers (Tr1 and Tr2) together with the resistor network R1 through R6 convert the main voltages to phase voltages. The conversion factor (the number of primary windings per number of secondary windings) of the transformers is 1:1.

Resistors R1, R2 and R3 must be scaled to match the voltage of the system in order for the ADC inputs not to exceed the maximum peak rating of 1 volt. ADC voltage maximum should be reached at maximum main voltage of the system front end. It may be assumed that the main voltage is equal for all three phases and, therefore, that the maximum input voltage to the converter, $\hat{u}_{IN}$, can be calculated from any one of the following:

$$\hat{u}_{IN} = \frac{R_4}{R_1+R_4} \times U_{PFS} \times \sqrt{2} = \frac{R_5}{R_2+R_5} \times U_{PFS} \times \sqrt{2} = \frac{R_6}{R_3+R_6} \times U_{PFS} \times \sqrt{2}$$

We assume a system where the phase voltage is 230V and, consequently, the main voltage 400V. The analog front end should allow for a 15% voltage overhead, as specified in IEC standards (see Table 1).

To achieve the ratings in Table 1, we start by defining resisters $R_4 = R_5 = R_6 = 1$ kohm, and get:

$$R_1 = R_2 = R_3 = \left[ \frac{U_{PFS} \times \sqrt{2}}{\hat{u}_{IN}} - 1 \right] \times R_4 = 380\text{kohm}$$

Using a standard valued resistor of 390 kohm, the maximum voltage for this configuration will be approximately 275V (i.e., about 390V peak amplitude). The voltage maximum should later be fine-tuned to 270V during factory calibration.

The above calculations may be repeated to adapt the design for any voltage system, but the maximum voltage of the meter front end must be considered when reading data or pulses from the meter. It should be noted that the default bit resolution of data registers and the meter constant of pulse outputs are based on a 270V maximum voltage.

It should also be noted that the DSP now measures phase voltages of a Delta-connected load. For example, the meter software of the ATEK5003 (The Evaluation Kit for the AT73C500 chipset) displays RMS voltage values with respect to the phase voltage and not the main voltage.

<table>
<thead>
<tr>
<th>Path</th>
<th>Node</th>
<th>Symbol</th>
<th>Nominal</th>
<th>Maximum</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase1</td>
<td>U₁</td>
<td>400</td>
<td>460</td>
<td>V₉₅₉₅</td>
</tr>
<tr>
<td></td>
<td>Phase2</td>
<td>U₂</td>
<td>230</td>
<td>270</td>
<td>V₉₅₉₅</td>
</tr>
<tr>
<td></td>
<td>Phase3</td>
<td>U₃</td>
<td>0.602</td>
<td>0.707</td>
<td>V₉₅₉₅</td>
</tr>
<tr>
<td>Voltage</td>
<td>Tr1/3 - GND</td>
<td>Uₚ₁</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tr1/4 - GND</td>
<td>Uₚ₂</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tr2/4 - GND</td>
<td>Uₚ₃</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>V₁₁</td>
<td>0.602</td>
<td>0.707</td>
<td>V₉₅₉₅</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>V₁₂</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>V₁₃</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tr3/Primary</td>
<td>I₁</td>
<td>-</td>
<td>80</td>
<td>A₉₅₉₅</td>
</tr>
<tr>
<td></td>
<td>Tr4/Primary</td>
<td>I₂</td>
<td>-</td>
<td>0.707</td>
<td>V₉₅₉₅</td>
</tr>
<tr>
<td></td>
<td>Tr5/Primary</td>
<td>I₃</td>
<td>-</td>
<td>0.707</td>
<td>V₉₅₉₅</td>
</tr>
<tr>
<td>Current</td>
<td>C4</td>
<td>Cl₁</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td>Cl₂</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C6</td>
<td>Cl₃</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
The Current Front End

Current transformers Tr3, Tr4 and Tr5 are used for sensing the phase current, which goes through the primary winding. The transformers should have a conversion factor, M, such that, at maximum rated phase current, the secondary current, which goes through the shunt resistors (R7, R8 and R9) does not produce more than 1-volt peak amplitude at the ADC input. The higher the conversion factor of the transformer, the lower the value of the shunt resistor and vice versa.

It should be noted that for high resistive values, the signal distortion in the current transformer is low, but the thermal noise in the resistor is high. On the other hand, for low resistive values, the thermal noise is lower, but the power dissipation of the resistor is higher. In addition, the current transformer may distort the signal if the load on the secondary winding is too high.

As a compromise, the example wiring uses current transformers with a conversion factor of 2500 and shunt resistors of 22 ohms. The full-scale current rating is 80A, at which the RMS voltage at the ADC input is:

\[ U_{IN} = R_7 \times I_1 + R_8 \times I_2 + R_9 \times I_3 = 22 \Omega \times 80A = 0.704V \]

The peak amplitude at the ADC input is then:

\[ u_{IN} = \sqrt{2} \times U_{IN} = 0.9956V \]

It should be noted that the current measured by the chipset is the main current. In a Start Connection, this is of no importance, since the phase and main currents are equal, but in the Delta-configuration this must be accounted for.

Measurement Method

The DSP uses the same calculation methods, regardless of type of connection, since there is no special mode setting for connecting the device to a Delta load. The differences in measurement method, as compared to the default Star connection are due to the wiring of the front end and the conditioning of signal amplitudes.

Using the front end connections illustrated in the schematic on page 7, the DSP will measure phase voltages and main currents for each phase. The measurement results, available via the data registers, do not necessarily give straightforward indications on the condition of the phase loads in a Delta connection. For example, the RMS values of phase voltages and main currents cannot be used to derive the power consumption of one phase load, since the Delta-wired load is connected between two phase nodes, as shown in Figure 3.

The DSP will give measurement results as if the load was connected in Star. Measurement results must therefore be related to the equivalent Star connection as shown in Figure 4. Please note that the load impedances of the equivalent connection are not the same as those for the actual Delta connection.

For example, the active power readings for phase one indicates how much power has been consumed in the equivalent load of Z1 and not how much power has been consumed in any of the true loads of the Delta connection.

Figure 3. The Delta-connected Load
Figure 4. Equivalent, Unbalanced Star Connection without Neutral Wire

Summary

In Delta-configuration, data registers should be interpreted as shown in Table 2.

Table 2. Delta-configuration

<table>
<thead>
<tr>
<th>Variable</th>
<th>Register</th>
<th>Measure</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>0</td>
<td>Active Power</td>
<td>Power consumed in equivalent phase load</td>
</tr>
<tr>
<td>P₂</td>
<td>1</td>
<td>Active Power</td>
<td>Power consumed in equivalent phase load</td>
</tr>
<tr>
<td>P₃</td>
<td>2</td>
<td>Active Power</td>
<td>Power consumed in equivalent phase load</td>
</tr>
<tr>
<td>Q₁</td>
<td>3</td>
<td>Reactive Power</td>
<td>Power consumed in equivalent phase load</td>
</tr>
<tr>
<td>Q₂</td>
<td>4</td>
<td>Reactive Power</td>
<td>Power consumed in equivalent phase load</td>
</tr>
<tr>
<td>Q₃</td>
<td>5</td>
<td>Reactive Power</td>
<td>Power consumed in equivalent phase load</td>
</tr>
<tr>
<td>S₁</td>
<td>6</td>
<td>Apparent Power</td>
<td>Power consumed in equivalent phase load</td>
</tr>
<tr>
<td>S₂</td>
<td>7</td>
<td>Apparent Power</td>
<td>Power consumed in equivalent phase load</td>
</tr>
<tr>
<td>S₃</td>
<td>8</td>
<td>Apparent Power</td>
<td>Power consumed in equivalent phase load</td>
</tr>
<tr>
<td>PF₁</td>
<td>9</td>
<td>Power Factor</td>
<td>Between main current and phase voltage</td>
</tr>
<tr>
<td>PF₂</td>
<td>10</td>
<td>Power Factor</td>
<td>Between main current and phase voltage</td>
</tr>
<tr>
<td>PF₃</td>
<td>11</td>
<td>Power Factor</td>
<td>Between main current and phase voltage</td>
</tr>
<tr>
<td>WPE</td>
<td>12</td>
<td>Active Power Exported</td>
<td>Total power in all loads</td>
</tr>
<tr>
<td>WPI</td>
<td>13</td>
<td>Active Power Imported</td>
<td>Total power in all loads</td>
</tr>
<tr>
<td>WQI</td>
<td>14</td>
<td>Reactive Power, Ind. Load</td>
<td>Total power in all loads</td>
</tr>
<tr>
<td>WQC</td>
<td>15</td>
<td>Reactive Power, Cap. Load</td>
<td>Total power in all loads</td>
</tr>
<tr>
<td>TIME</td>
<td>16</td>
<td>Time Since Reset</td>
<td>Not affected</td>
</tr>
<tr>
<td>FREQ</td>
<td>17</td>
<td>Line Frequency</td>
<td>Not affected</td>
</tr>
<tr>
<td>U₁</td>
<td>19</td>
<td>RMS Voltage</td>
<td>Phase voltage</td>
</tr>
<tr>
<td>U₂</td>
<td>20</td>
<td>RMS Voltage</td>
<td>Phase voltage</td>
</tr>
<tr>
<td>U₃</td>
<td>21</td>
<td>RMS Voltage</td>
<td>Phase voltage</td>
</tr>
<tr>
<td>I₁</td>
<td>22</td>
<td>RMS Current</td>
<td>Main current</td>
</tr>
<tr>
<td>I₂</td>
<td>23</td>
<td>RMS Current</td>
<td>Main current</td>
</tr>
<tr>
<td>I₃</td>
<td>24</td>
<td>RMS Current</td>
<td>Main current</td>
</tr>
</tbody>
</table>
Typically, it is of no importance if the individual phase powers reported are relative to a Star or Delta connection, as long as the overall power readings are correct. Regardless if the chipset is wired to a default Star load or the Delta load, as illustrated in the schematic on page 7, the overall power readings are always obtained by summing the individual phase registers.

When wired to a Delta load, it must be noted that individual phase power information is correct only in the special case when both the generator and the load are balanced. If the load or supply is unbalanced (even if the generator is balanced, impedances in the transmission lines may result in unbalanced voltages), then only the sum of the individual phase power readings will be valid for the Delta connection. Individual phase powers cannot be evaluated for an unbalanced Delta load.
Figure 5. Front End Connection Schematic