Turbine Power Meter

A Hardware Design for the uPD78F9418A Processor and the Cornelius Van Drebbel Design Contest

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1. Introduction

1.1. Description of the application and its purpose

The use of alternative energy sources on the frontier is well known and many devices exist to develop electrical power from such sources as sun, wind, tides, running water, and even decomposing waste material. Sometimes these power sources can be more economical than the vast electrical power grid that spans our nation and much of the world. Here in the Dallas, TX area we are adequately served by an abundance of both natural resources and commercial power generating facilities. However, when my son leased land in the area for a cattle operation the economics of providing electrical power for containment fencing dramatically shifted the viable options to the alternative power sources. These were further narrowed to either solar or wind sources and cost eventually favored wind generation. Eventually, solar and backup fossil fuel generation will be incorporated so that a well-balanced and self-sustaining capability will result. **Figure 1** shows a system diagram of a potential use for the TPM.

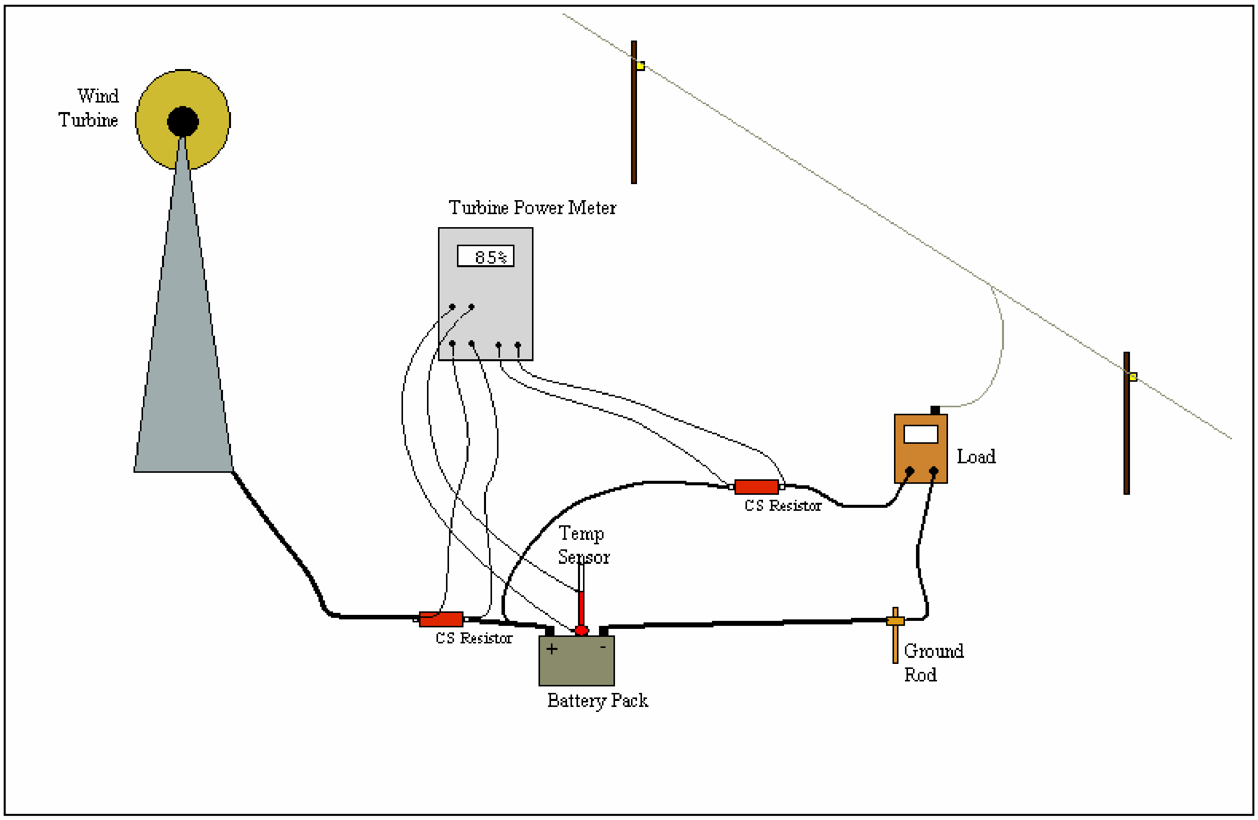

Figure 1- Turbine Power Meter System Diagram

In an effort to determine the capacity and state of the power generation and storage plant, a power meter that would measure the contribution of several sources and sinks was deemed valuable. Battery capacity and energy supplied to and demanded from the plant are important metrics that need to be measured and tracked. These metrics can be used to calculate capacities and alternative power scheduling options when the primary means are not adequate (The wind does not always blow around here). Economic factors can also be evaluated and assessed more accurately with real data to reinforce them. The development of an inexpensive, flexible, and configurable power meter for these types of applications looks like a promising market with alternative energy sources becoming more prevalent.

The Turbine Power Meter (TPM) is an integrated collection of hardware and software modules used to provide a measurement of the amount of power and energy developed and supplied in an alternative energy generation plant. The TPM consists of sensors connected to the power generating and consuming elements of the system, environmental sensors (e.g., temperature), load actuators to protect the system, and the processing and display elements to properly monitor the power plant. Sensor conditioning modules are included that scale, integrate, and calculate the voltage and power associated with those sensors. A microcontroller and its software accumulate these data, scale, and display them in an understandable terminology.

1.2. Design considerations

Several items must be considered to properly implement the TPM.

1.2.1. Sensor Integration

In a wind turbine system, the power is supplied to the load and storage units in a pulsed, direct current (DC) format. Often the load, in this case an electric fencer running off a 12V inverter, represents a highly time varying demand. Since a battery is the primary storage device in the system, the voltage remains constant and the current pulses as power is supplied or received. Figure 2 shows the voltage across a current sensor for a battery supplying power to a 150W power inverter driving a 30W electric fencer as a load. The highly variable nature of these waveforms makes integration in the analog domain desirable. Aliasing effects are averted and narrow spikes in the waveforms containing non-negligible energy are accumulated.

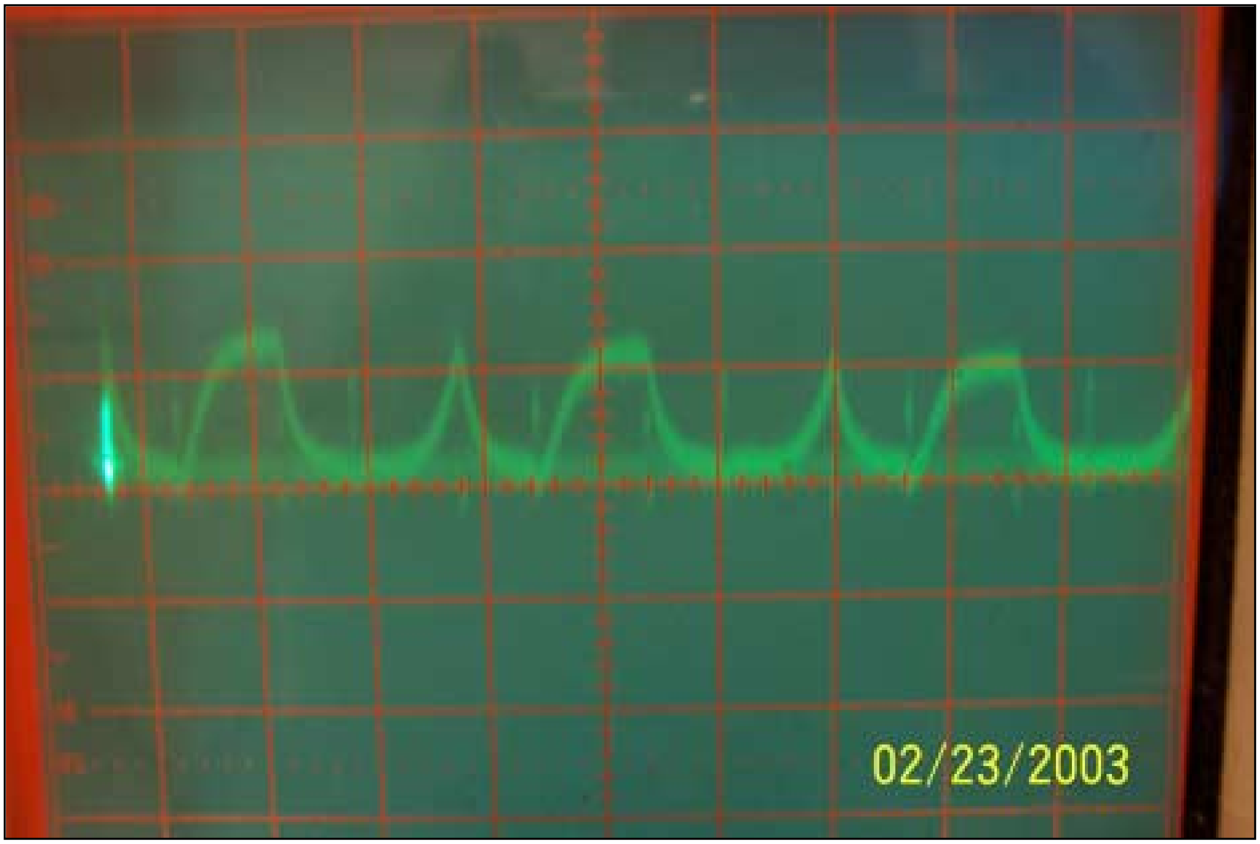

Figure 2- Example of Fencer Current Load

1.2.2. Power Measurement Sensors

In order to keep from overburdening the uC in this measurement task, integrating power sensors were developed. The MAX4210 series of power monitors prove beneficial as they measure both current and voltage in a high-side arrangement and multiply the result on-chip to deliver a voltage measurement proportional to the power its input represent. These integrated circuits multiply the high-side current measurement by its sensed voltage and develop an output voltage proportional to the power these measurements represent.

1.2.3. Sensor Measurement Range

This system must measure voltages in the 0-24V range and currents in the 0-100 ampere range. Current shunts such as those manufactured by Deltec Co. (Figure 3) are used to provide a calibrated voltage to a rated load current. The shunt rating is stored in a portion of the sensor data structure in the uC to allow conversion of the measured values into the proper engineering units.

Figure 3- Deltec MKA Series Current Shunt

1.2.4. Energy Storage Level

The energy level in the storage device is an important attribute that needs to be measured and displayed. This is a very active area in device manufacturing and several companies are trying to make devices to accurately gauge the energy level of battery systems. However, most of these are targeted at the laptop PC market and are not sufficient for the agricultural/industrial market, yet. The TPM will endeavor to measure the energy level of the system battery using a combination of coulomb counting and voltage level. These efforts are targeted at trying to obtain the battery open-circuit voltage level that is a standard means of deducing battery capacity. Temperature is also an important metric in this determination.

1.2.5. Units Conversion

The primary use of the TPM is to measure and display the amount of energy flowing through the system it is attached to. This is done by measuring the energy provided or used by each element of the system. The TPM can then display how much energy was supplied by the generating units (e.g., wind or solar) and how much was used by the loads (e.g., fencer, diversion loads, etc.). In order to make the TPM user-friendly, common energy units such as watts or watt-hours will be displayed to the user.

1.3. Specific functions used in the microcontroller

The TPM was developed using the NEC KORE9418 development board that contains an NEC uPD78F9418A microcontroller (uC). This computing platform was chosen because it was a very efficient platform for the task at hand. The uC has adequate programming space, RAM, and integrated peripherals. The KORE9418 development board is a compact and convenient platform for both prototyping and integration into the final product. Most of the integrated peripherals of the uPD78F9418A are or will be used in this design. ADC channels are used to measure system voltage and power, the Serial module is used for communications to a user/developer terminal, and the keypad interface is used for simple operator control. Timers are used to schedule the power measurements, the watch timer is useful for the user interface, and the LCD interface is used for stand-alone operational display of the processing variables under measurement. Additionally, the K0S-MM monitor program supplied with the development system has been leveraged to provide the Serial port interface. The K0S development tools are complete, powerful, and adequate for development with the processor family. I was not able to plumb the depths of the power behind all these facilities, but hope to as this design continues to evolve.

2. The Turbine Power Meter

This section describes the implementation of the TPM.

2.1. Block Diagram

Figure 4 shows the block diagram of the system. It consists of high-side current shunts that can be used to measure currents and voltages. These shunts are processed by the sensor conditioning analog circuitry to provide voltage levels proportional to the energy at the shunts over a short time period. The analog integration time period was chosen to be 13.7ms which allows for convenient digital accumulation of the ADC values to build up to a watt-hour value. The output of the analog sensor conditioning is measured by the ADC channels of the uC. The uPD78F9418 has 10-bits of resolution that is adequate to cover the measurement range. This 10-bit value is carried throughout the system. The ADC values for each sensor are accumulated in two levels. The first level is a 64 value accumulator which can be appropriately scaled to yield an instantaneous watt measurement for each power channel. The second level accumulates the equivalent of 64x64x64 ADC values to yield a scaled measurement of a watt-hour. The number of samples made at this level is also tracked so that the number of hours that this measurement represents can be displayed. The sensor data can be displayed on a user terminal using the K0S-MM commands developed for this unit. This data can also be displayed on the LCD display if it is activated by the user through the keypad interface.

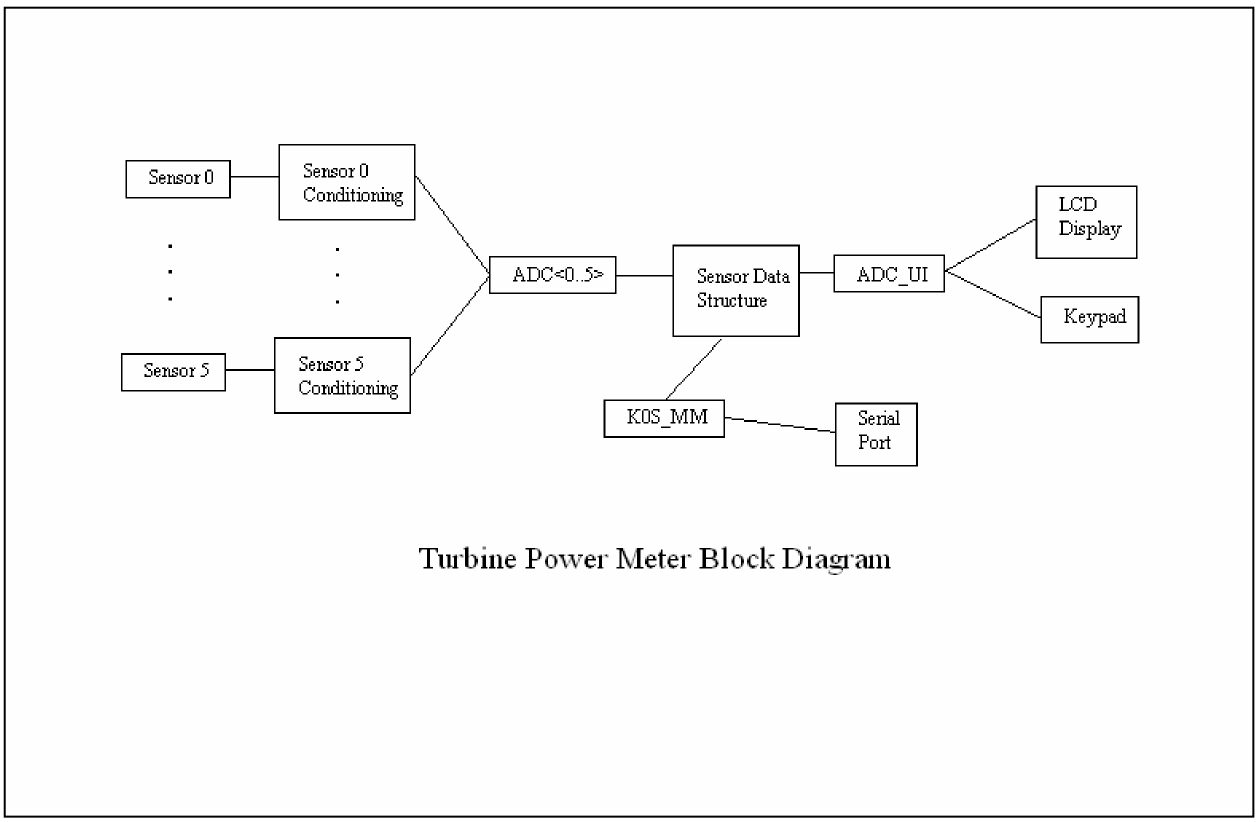

Figure 4- Turbine Power Meter Block Diagram

2.2. Schematics

The TPM consists of a main board (TPM main board) and 1 or more sensor modules which plug into the main board. Current shunts are connected at various points in the power plant and are not shown. These shunts are cabled to the TPM main board through a connector to the TPM enclosure. These signals from the current shunts are routed to the dual-sensor modules were the sensor data are conditioned. The outputs of the dual-sensor modules then go the ADC channels of the KORE9418 board

2.2.1. Main Board (TPM-Main Board)

The main board consists of a power supply section, sensor conditioning section, KORE9418 module, keypad, and LCD module.

2.2.1.1. Power Supply

The sensor conditioning section of the TPM requires 3 power supplies: +5V, +6V, and –5V. The KORE9418 is supplied with +5V. The power supplied to the TPM must be between 9-20Vdc. Separate terminals are provided to allow the TPM to be powered separately from what it is monitoring. However, the TPM ground must be the same as the system ground for proper operation. The TPM provides the proper operating voltage by using the MAX667 For +5V and +6V, and the MAX889 for the –5V supply.

2.2.1.2. Sensor Conditioning

The sensor conditioning section of the TPM main board consists of the sensor connector, three dual-sensor modules, and diode protection of the integration signal, I<0..5>. These diodes prevent the integrator signals from going outside the allowable levels of the KORE9418 ADC channel inputs and damaging it.

2.2.1.3. KORE9418 module

The KORE9418 development board is easily attached to the TPM main board using either a set of pins for solder connection or pins and connector to allow plug in replacement. This module is used to process the conditioned sensor data, control the LCD module, and interface to the user through the Keypad or the serial interface.

2.2.1.4. Keypad

The keypad consists of two momentary contact push buttons that are used to sequence through the TPM command and display menu allowing the user to configure and display various data from the TPM. They interface directly to the KORE9418 board.

2.2.1.5. LCD Display

The KORE9418 is directly connected to an 8-10 character LCD for data display. All signals to control the LCD are provided by the KORE9418 module. This display is used in the absence of a terminal to communicate measurement and calibration data to the user via the TPM control program.

2.2.2. Dual Sensor Module (TPM- Dual Sensor w SPST-POT)

The Dual Sensor Module receives sensor data from the S<1,2>+ and S<1,2>- connectors and processes these signals to form an output voltage proportional to the energy it senses. Module 0 (TPM- Dual VC Sensor w SPST-POT) is a special Voltage/Current sensor where the S1+ and S1- terminals are connected between the power in and system ground, respectively. Throughout the system channel 0 (as it will be denoted) represents the system voltage for power scaling operations. Its inputs bypass the MAX4210 and connect directly to the AD628 for integration (smoothing) and scaling.

2.2.2.1. MAX4210 Power Monitor

The MAX4210 Power Monitor is used to convert the voltage developed by the current shunts into a voltage representing the power at its V_{RS} terminals. It is capable of developing this power signal from common-mode voltages ranging from 0-28V with differential voltages of 100-150 mV (depending on model) representing full-scale. Its output ranges from 0-+5V.

2.2.2.2. AD628 Difference Amplifier

The AD628 Difference Amplifier is a versatile device that is used to both integrate the power output of the MAX4210 and scale the output to the range of the KORE9418 ADC.

The integration is operation is provided by the capacitor connected to the C_{FLT} & V_{REF} pins. Integrator reset action is provided by the MAX4514 analog switch as controlled by the KORE9418 through the R<0..5> signals.

A potentiometer is used to calibrate this gain so that the resulting energy levels have an accurate physical significance. Eventually, this potentiometer will be replaced by a digital version connected to the KORE9418 via an I^2C bus. This will allow the KORE9418 to perform auto-calibration.

2.3. Software

The uPD78F9418 uC is programmed for the KORE9418 development board to process the sensors' data and to develop values equivalent to instantaneous power(watts) and accumulated power or energy (watt-hours). These data are made available to the user through the K0S-MM monitor program and the Keypad/LCD of the User Interface. The software developed from the K0S-MM program is separated into two modules: the TPM.ASM main program ad the K0S_MM.ASM Monitor module.

2.3.1. TPM.ASM- Main module

This is essentially the K0S_MM main loop, initialization, and interrupt vector table.

2.3.1.1. Initialization

Some changes were made in pin initialization and calls inserted for TPM and Monitor initialization. Global interrupts are enabled in this section.

2.3.1.1.1. Port_Init

This routine initializes the pins to a known value that may later be changed by other modules.

2.3.1.2. Interrupt Processing

No interrupt processing occurs in the program, but the interrupt vector table is fully populated here.

2.3.1.3. Main Loop processing

The main process cyclically calls the TPM main routine (TPM_PROC) and then the K0S_MM monitor main routine (MMON).

2.3.2. TPM_P.ASM Sensor Processing Module

2.3.2.1. TPM_INIT- Initialize the TPM program

The TPM_INIT routines initialize all sections of the TPM. It begins by configuring and initializing the I/O pins for Presence, Sensor reset, and sensor data. Watt and watt-hour counters and error flags are then set up, followed by a call to detect how many sensor modules are present in the system (NUM_SENS). This is followed by the initialization of the sensor conversion value which will eventually become a part of the configuration routine, but for the present may be adjusted by the Monitor as needed. After this, The ADC is "warmed up" by cycling it quickly a number of times for all active channels. This is followed by initialization of the Sensors' data structures. Once this is accomplished for all the active sensors, a call is made to allow the user interface (ADC_UI) to display data, and then the sampling interrupt timer is initialized and enabled (SAMPINT_INI). However, global interrupts are not yet enabled. This is done in the main control module, TPM.ASM (MAIN). This structure was used to integrate the K0S_MM monitor program into the system as easily as possible.

2.3.2.1.1. SAMPINT_INI- Initialize the Sample Interrupt timer

Initialize timer to provide interrupts at 13.7ms (full period). This period allows the first 64 samples to be a fairly close representation of the instantaneous power (watts) of the system, while 64x64x64 (262144) samples equal 3600 seconds or one hour for simpler energy (watt-hour) measurement conversions. Thus, a register may be set up to accumulate watts and another set up to accumulate watt-hours.

2.3.2.1.2. NUM_SENS- Determine the number of sensor modules installed

Determine number of sensor modules installed in the TPM. This routine scans the Dual Sensor module's Presence bits to determine how many modules are connected to the unit. Each presence bit represents two sensors with a maximum of six analog sensors in the system. This module scans the presence bits starting with the highest to the lowest (/PR2 down to /PR0) and when the first active presence bit is found the system is configured for this number of sensors. Thus, sensor modules are added from the lowest to the highest in presence values. Additionally, sensor 0 is dedicated to be a voltage sensor whose nominal value is used to calculate the power measured by the sensor.

2.3.2.2. SAMPINT- Processing the sampling interrupt

Power Meter Timer ISR- This routine is run whenever the sampling timer expires and insures that the sensors are handled in a uniform and timely manner. This is especially important since the sensors are interfaced through an integration scheme that is based upon uniform reset and sampling control.

2.3.2.2.1. ADC_Sample- Sample the ADC for all sensors

Sample all the ADCs as fast as possible. This routine samples the ADC channels serially, converts the data result from 10-bit "top justified" data to 10-bit "bottom justified" data, and inserts it into the Sensor data structure. Several development hooks allow direct access to the ADC channel data.

2.3.2.2.2. ADC_Reset- Reset the sensors' integrators

Reset the integrators of all the Sensors as fast as possible. These digital outputs go to pins that in this case close analog switches that reset the Sensor's integrators. This effectively terminates the sensor's measurement.

2.3.2.2.3. ADC_Integrate- Remove reset on the sensors' integrator

Enable the Sensors to integrate as fast as possible. These signals open the sensor's analog switches enabling them to integrate the voltage and power signals developed by the sensors. Integration was chosen so that no important data would be lost in the measurement process. The use of the MAX4210 power monitor greatly simplifies the task of measuring power.

2.3.2.2.4. ADC_Update- Update the sensors' data structure with new ADC sample

Update the 64 bit ADC accumulation based on new data sample. System timing is set up to simplify the development of the watt-hour measurement. However, by accumulating 64 samples of ADC channel data a accurate approximation of the instantaneous power output (in watts) may be obtained. The 64 data samples represent ~0.87890625 seconds and by applying a scale factor to this data of (146/128) a Watts measurement will result. Accumulating 64x64 (4096) of these samples results in 3600 seconds or 1 hour of measurement which make the energy calculation to watt-hours simpler. This routine tests to see if 64 samples have been accumulated in the 64 sample ADC accumulator. If there have been, it calls the Update_WHRS routine to update the watt-hour accumulators and reset the 64 sample ADC accumulators.

2.3.2.2.4.1. Update_Watts- Update the Watts values with new ADC data

This routine cycles through all the active sensors and accumulates the latest sensor sample with the 64 sample ADC accumulation value for that sensor.

2.3.2.2.4.2. Update_WHRS- Update the watt-hour values with new data as required

This routine captures a "snap-shot" of the 64 sample ADC accumulator and resets it and its sample counter as quickly as possible so that the watt level data will remain stable for ensuing watt processing. It then updates the Watt-Hours accumulation registers based on the Watt register.

2.3.2.3. TPM_PROC- Process the turbine power meter program

This is the main background routine of the TPM process. It monitors any requests to the User Interface.

2.3.2.3.1. ADC_UI- ADC channel User Interface

This routine displays the sensor data in a periodic manner. The number of samples is masked and compare to a value required enabling the printout. The display contains the number of samples acquired to date, and each sensor's data. This data consists of the latest sample value, the watt accumulation, and the 32-bit, watt-hour accumulation. The period of this output is set up by the FREQ_MASK and the UI_OUTPUT_CNT constants.

2.3.2.3.2. Display_Values- Display the values in the sensor data structure

This routine displays the latest sample, watt, watt-hour, and hour values associated with the ADC channel specified to the serial port.

2.3.3. K0S_MM.ASM Monitor Module

An in-depth discussion of the K0S_MM Monitor module is beyond the scope of this work. However, several TPM commands have been added to extend its usefulness to the TPM and it is a valuable user interface and diagnostic tool.

2.3.3.1. Initialization

Changes were made to segment K0S_MM pin assignments from those pins available for other modules.

2.3.3.2. Interrupt Processing

No changes were made in this area.

2.3.3.3. Main Loop Processing

Small changes were made to make the program flow more modular. In addition, TPM specific commands were added referencing associated routines in the TPM_P.ASM module. These are described below.

2.3.3.3.1. TPM_TB- Display Turbine Battery Voltage

Display Turbine Battery Voltage- the ADC value is scaled by the sensor's scale factor and adjusted for the sensor's calibration target. Engineering units are "Volts". This measurement is assigned to ADC channel 0 which is ASSUMED to be connected to the system's battery voltage.

2.3.3.3.2. TPM_TI- Display Turbine Input power

Display Turbine Input Power- This routine displays the power input from the turbine. For now it is ASSUMED to be connected to ADC Channel 1. These values are developed and displayed using the Display_Values routine. Its engineering units are "watts" and "watt-hours".

2.3.3.3.3. TPM_TO- Display Turbine Output power

Display Turbine Output Power- This routine displays the sum of the ADC channels 2-n which, for now, are assumed to be power sinks. Its engineering units are "watts" and "watt-hours".

2.3.3.3.4. TPM_TT- Display Turbine Total resultant power

Display Turbine Total Power- this routine displays the total power of the turbine system. It is the turbine input power minus the sum of the power output to all the sinks. Its engineering units are "watts" and "watt-hours". these values represent the instantaneous power and accumulated energy for the number of hours displayed.

3. Summary

The Turbine Power Meter (more aptly named Energy Meter) is still a work in progress and not a completed project. Prototyping is under way and no real work has been done on the User Interface especially with regard to the LCD and Keypad. I am sorry that the documentation did not include the software flowcharts that you specified. Please forgive me.