

Distributed Power Control Architecture With Multiple MCUs Over FSI

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ABSTRACT

Distributed power architecture (DPA) has been widely used in many complex systems that require multiple power and voltage levels. DPA approach allows modular power converter design and, hence, enables general economies of scale, allowing manufactures quickly implement power conversion solutions with a wide range of output power and output voltages. This white paper discusses the application of C2000 microcontrollers (MCUs) in implementing control of such DPA systems. The control approach discussed here essentially implements a very flexible distributed power control architecture (DPCA) using multiple C2000 MCUs, taking full advantage of its control optimized high speed C28x CPU, flexible control peripherals and a new communication module, called the fast serial interface (FSI). Such system level solution can be advantageous in applications like solar string inverters, off-board EV chargers and any other distributed DC/DC or AC/DC applications. First, this document provides an overview of C2000 MCU-based distributed control of such power conversion systems and then presents an example case study of DPCA using the solar string inverter application.

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1 Introduction

The design advantages of distributed power [1] have helped it spread to industrial controls, data communication, telecom and every application that uses complex systems with a requirement for multiple power and voltage levels. There was a time when the predominant power supply architecture consisted of a centralized power unit that distributed power throughout the system via a network of cables and supply bus bars, but as power demands have changed, so have system power topologies. Driven by increasing power consumption and a need for better supply performance, in conjunction with the availability of wide bandgap GaN and Sic products, more sophisticated power distribution architectures are being implemented today. The modern distributed power architecture (DPA) can spread the concentration of heat throughout the system, support high currents at different voltage levels and provide excellent transient response to rapidly changing loads. DPA architecture is widely used in AC/DC rectifier application where the front-end AC/DC power supply covers the power needs of the entire system. Then the required DC/DC stages are controlled locally in order to achieve high efficiency and improved static and dynamic performance. This way all the subsystems DC/DC connect to a single DC bus making it easier to design and upgrade the sub-systems.

DPA concept is also being increasingly used today in fast DC charging application because it enables modular design and allows adjusting to a wide range of output voltages. Here again a front-end power factor correction (PFC) stage, such as a three phase Vienna PFC, provides the high voltage DC bus which is then used to power multiple DC/DC stages that finally charge the battery. The modular approach makes it possible to achieve economies of scale for manufacturers, enabling them to reuse existing sub-units and design blocks when addressing new customers. In the event of a failure, the modular approach also simplifies maintenance and repairs. With the push towards shorter charging times the total power that is needed in a DC charger increases significantly. Consequently, the power delivered by each sub-unit and design block in a DC charger goes higher to provide a balance between performance, power, and ease of use. The sub-units themselves are based upon efficient multi-level, multi-phase topologies allowing heat generation to be spread across the available volume, as well as enabling scalability. The modular approach also enables general economies of scale, enabling manufactures to quickly implement a wide array of charger output powers as market demands develop.

Similar DPA approach is also being used today in solar inverter and energy storage systems (ESS), specifically, in solar string inverters with ESS. For the solar string inverter with or without ESS capability, the load-end DC/AC inverter supply covers the power needs of the entire system while achieving high efficiency and improved static and dynamic performance. Then the front-end DC/DC stages are operated locally in order to achieve high efficiency, optimized maximum power point tracking (MPPT) and other features, such as, rapid shutdown control. Common factors that impact energy production in a solar inverter include shading, different module types and orientations or large temperature fluctuations. In this case a distributed architecture can increase energy production largely due to having the maximum power point tracking (MPPT) capability at each dc/dc stage. The DPA architecture also provides obvious advantage of increased uptime for string inverters. Since string inverters are converting less power for fewer panels, if one string fails, the whole array's energy is not lost, just the power from that string. The same applies when inverters need to be disconnected for preventive maintenance of system components. Also, during scheduled maintenance of system components (excluding the inverter stage), the array can be turned off in smaller sections, which further increases uptime.

Thus, with overall goals of cost effectiveness, scalability, modular design, high efficiency, optimize operation and fast static and dynamic performance DPA provides obvious advantages in many AC/DC, DC/DC and DC/AC power conversion applications.

C2000 microcontrollers (MCUs) with its control optimized high speed CPU, flexible control peripherals and fast serial interface (FSI) is a perfect fit for implementing distributed digital control of such DPA systems. Multiple C2000 MCUs can be used to control multiple power conversion stages and then all the MCUs can establish a very fast communication link between them using their FSI ports. This approach essentially implements digitally controlled flexible distributed power control architecture (DPCA) for many DPA systems. The new FSI module is a serial communication peripheral capable of reliable high-speed communication across isolation devices. It provides a higher speed, lower latency, noise tolerant signaling across isolation with built in error detection and correction. It provides variable packet size (2 to 32 bytes, not meant for large data transfer) and so ideal for bytes of data transfer between control loops in a DPCA system. With embedded data robustness checks, data-link integrity checks, skew compensation and integration with control peripherals, the FSI module can enable high-speed, robust communication in any DPA system and thus allows implementation of distributed power control architecture (DPCA).

2 Distributed Power Control Architecture

This section discusses different applications where the C2000-based distributed digital power control architecture (DPCA) can be used to achieve modular and flexible power designs.

2.1 Distributed Power Control Architecture – DC/AC System

The first DPCA application is illustrated in [Figure 1](#). This is the C2000 MCU-based solar string inverter DPCA system where the photovoltaic (PV) string output is processed through a MPPT DC/DC converter and then applied to the DC/AC inverter inputs. The inverter finally delivers power to the grid. As indicated in [Figure 1](#), all DC/DC and DC/AC power conversion stages are controlled by multiple C2000 MCUs. A key feature of such PV system is the efficiency of conversion at which the power converter stage can extract the energy from the PV arrays and deliver to the load. The maximum power point tracking (MPPT) of the PV output for all sunshine condition allows reduction of the cost of installation and maximizes the power output from the PV panel. Therefore, the DC-DC converter employs some MPPT algorithm to efficiently extract the PV output power and convert the PV output voltage to a high voltage DC bus. The converter draws dc current from the PV panel such that the panel operates at its maximum power transfer point. This requires maintaining the panel output, such that, the DC-DC converter input at a level determined by the MPPT algorithm. The DC-DC converter, depending on the system requirement, can use either an isolated power stage or a non-isolated stage. This is most frequently implemented using an interleaved boost or multi-level boost converter stage. The high voltage bus from the DC-DC converter is then used to power the DC-AC inverter that eventually supplies the load and connects to the grid. Depending on the power level of the string inverter the MPPT DC/DC could consist of multiple power stages controlled by multiple C2000 MCUs. Then all of the MCUs, as indicated in [Figure 1](#), could be connected through the high-speed FSI ports for exchange of information between the DC/DC and the DC/AC stages. This exchange of information could be anything related to closed loop control, system parameter monitoring and other system level management functions needed to support the proper operation of this solar inverter DPCA system.

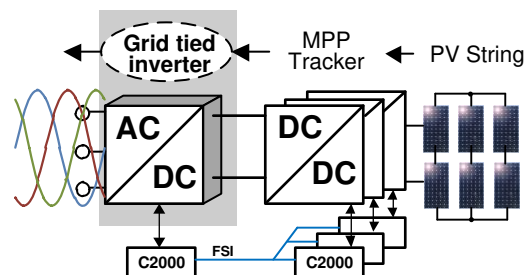


Figure 1. Solar String Inverter in a DPCA Configuration

Figure 2 shows the same solar string inverter DPCA system as in Figure 1 with the added energy storage feature. This makes it an energy storage system (ESS). All DC/DC and DC/AC power conversion stages are controlled by multiple C2000 MCUs. For the ESS with string inverter, the grid-tie converter indicated in Figure 2 needs to be bi-directional. Also a second bi-directional DC/DC is needed between the energy storage device, such that, the battery, and the high voltage DC bus. Here again, based on the power level of the ESS, the DC/DC could consist of multiple power stages controlled by multiple C2000 MCUs and then all the MCUs could be connected through the FSI ports for overall system control and management.

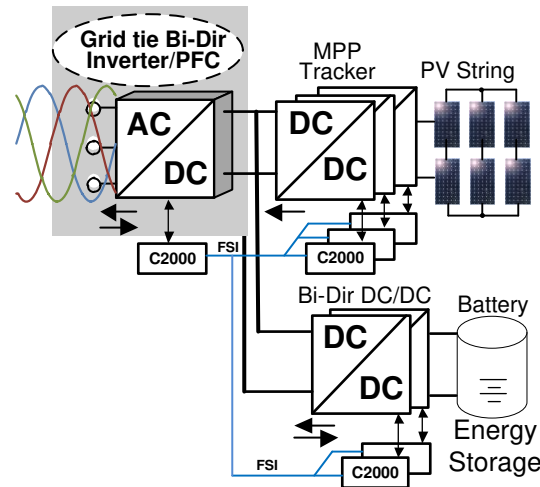


Figure 2. Solar String Inverter With Energy Storage in a DPCA Configuration

2.2 Distributed Power Control Architecture – AC/DC System

Figure 3 illustrates the DPCA configuration for a fast DC charging application for electric vehicle (EV). Most of the modern off-board fast chargers have a power rating of 50 kW to 135 kW which allows battery recharging in less than 30 minutes. New 150 kW fast chargers have also been announced with 350 kW chargers as a part of long-term plan. These commercially available fast chargers are powered from 208/480 V three phase input. This is implemented with a 3 phase PFC, such as a Vienna PFC, followed by a DC/DC as illustrated in Figure 3. The DC/DC converter, usually a resonant topology, provides an efficient means of interfacing the output DC bus voltage from a three phase Vienna rectifier/T-type rectifier to the battery of an electric vehicle. The phase-shifted full-bridge topology with the SiC devices also constitutes an alternative solution for the DC/DC stage. A single C2000 MCU could be used to control the Vienna PFC and single or multiple C2000 MCUs could control multiple DC/DC stages. Then, all the MCUs could be connected through the FSI ports for overall system management. For more details on C2000 MCU-based Vienna PFC and EV charging DC/DC control, see the [Vienna Rectifier-Based, Three-Phase Power Factor Correction \(PFC\) Reference Design Using C2000™ MCU](#) and the [Bidirectional CLLLC Resonant Dual Active Bridge \(DAB\) Reference Design for HEV/EV Onboard Charger](#), respectively.

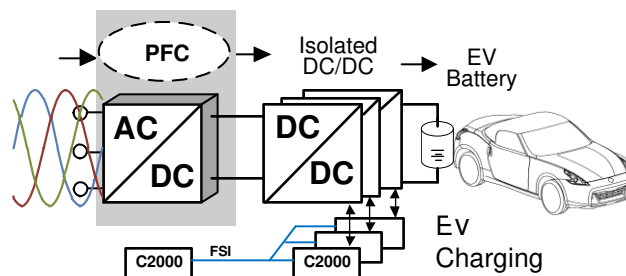


Figure 3. Fast DC Charger for EV in a DPCA Configuration

The fast DC charging system illustrated in Figure 3 shows some limitation in high power EV charging applications. When implemented this way the overall system efficiency, including the service transformer (that provides the 208/480Vac input), is very low (about 93%). In addition to this, the overall size, weight and the installation cost of such a system is very high when the power rating is high to enable fast charging.

An alternative approach is to use Solid-State Transformer [3] (SST) technology to directly connect the fast charger to the 2.4 kV Medium-Voltage (MV) single-phase line. This avoids the use of service transformer, improves efficiency and significantly reduces the installation costs. However, due to the relatively high voltage (2.4 kV ac) at the converter input, a modular design approach needs to be adopted if commercially available Silicon Carbide (SiC) devices are to be used. One example is the Multi-Cell Boost (MCB) topology with three input-series-output-parallel (ISOP) connected dc/dc converter modules as shown in Figure 4. This is adopted for the fast charger application due to its high power density, high efficiency, low cost, low number of switches and expected high reliability.

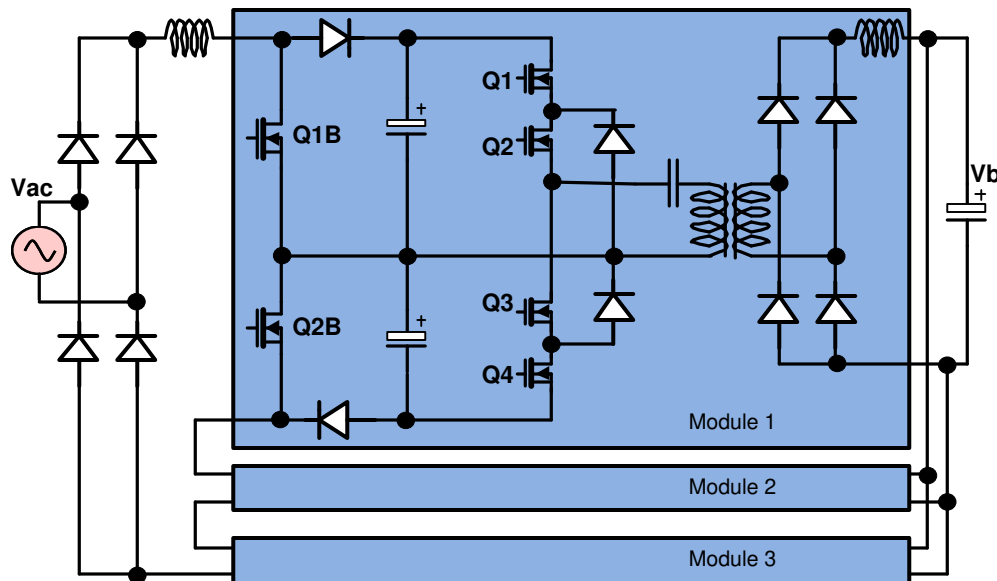


Figure 4. Input-Series-Output-Parallel Multi-Cell dc/dc for fast EV Charger

By using this topology, the losses can be reduced significantly compared to the state-of-the-art solution with low-frequency transformer and three-phase PWM rectifier as shown in Figure 3. This topology has additional advantages such as independent control of input and output stages, a relatively simple control strategy for dc bus capacitor voltage balancing and the reduction of the input and output inductors by interleaving the 3-level boost converters at the input side and the NPC converters at the output side. The ISOP configuration of the adopted MCB topology modules enables scalability in both the input voltage and the output power ratings. Here again, based on the power level of the fast charger and its input voltage ratings, the ISOP configuration could consist of multiple power stages controlled by multiple C2000 MCUs and then the MCUs can be connected through the high speed FSI ports to form a fast EV charging DPCA system.

Figure 5 shows the isolated/non-isolated off-line AC/DC DPCA system where the input AC voltage is rectified through a PFC stage and then applied to the high frequency isolated DC/DC converter. The PFC stage draws sinusoidal input current in phase with the input voltage in order to maintain high power factor (PF) and low THD input current and provides a regulated high voltage DC output to the DC/DC stage. The DC/DC stage generates an isolated low voltage DC output with tight regulation and fast transient response against fluctuations in input voltage and output load current. Such AC/DC system is usually controlled by single or dual C2000 MCUs. However for higher power level both the power conversion stages could consist of multiple converters controlled by multiple C2000 MCUs. All the MCUs can then be connected through the high speed FSI port for overall system management.

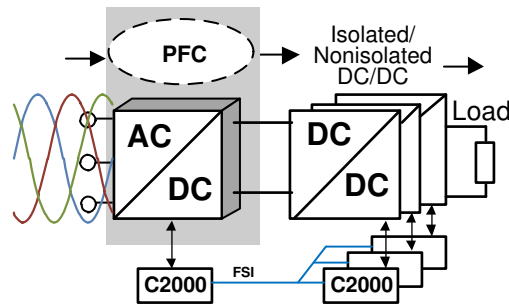


Figure 5. Off-Line AC/DC Power Supply in a DPCA Configuration

2.3 Distributed Power Control Architecture – DC/DC System

Figure 6 illustrates a DC distribution [4] used in many industrial systems. Industrial plants demand highly reliable supply of power. The loads in these plants are sensitive to power supply disturbances. DC distribution addresses some of these challenges. Such dc systems use power converters to convert ac source(s) to dc and distribute the power using dc lines. DC/AC converters are used at the load end when it is required. For the motor type loads, driven by inverter drives, DC voltage is directly applied to drive inputs.

The power converters are the main components of such DC systems. The fast response capability of these converters facilitates use of alternate power sources to provide highly reliable supply of power. The alternate power sources in combination with power converters also provides a very effective method for meeting the ever-increasing high-power loads in certain applications such as, on ships that also need highly reliable and very high-quality power supply. For this kind of applications the conventional ac systems are very hard to maintain. The power converters in the DC system also provide very effective filtering against power disturbances. The fuel-cell technology is another driver for dc distribution, as the fuel cells produce dc power. Thus, the dc distribution becomes attractive for many industrial systems with heavy motor controlled loads and/or sensitive electronic loads.

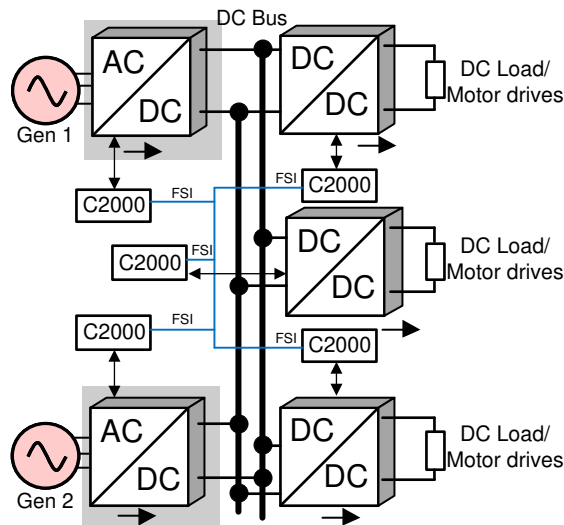


Figure 6. DC Distribution System in a DPCA Configuration

Here again, multiple C2000 MCUs could be used to control the power converters, and then, all of the MCUs could be connected through the FSI ports for overall system management.

3 DC/AC System - Power Topologies

Although DPCA can be used in any DC/DC, DC/AC or AC/DC system where modular design is necessary, however, this document discusses DPCA in detail using only a solar string inverter example. Therefore, this section discusses a few topologies used for solar string inverter application, briefly discuss their control using C2000 MCU, and then lists the peripheral resources needed for a C2000-based control. [Section 4](#) and [Section 5](#) discuss how a C2000-based DPCA can be realized for solar sting inverter system.

3.1 MPPT DC/DC Stage

[Figure 7](#) illustrates a C2000-based MPPT DC-DC converter control used in solar string inverter application. PV panel output voltage, V_p , is applied to the DC/DC input stage. This DC/DC stage illustrates conventional 2 phase interleaved boost topology.

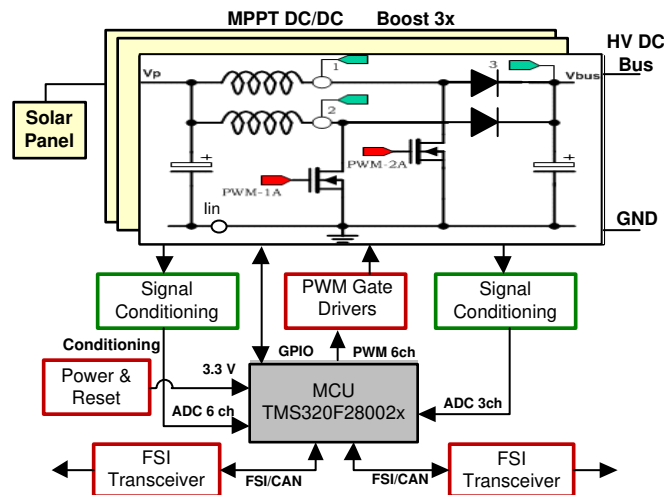


Figure 7. MPPT DC/DC Boost Control Using C2000 MCU

[Figure 8](#) shows the same MPPT DC/DC control using a 3 level boost topology. In both cases three boost stages are shown to be configured in parallel and controlled by the same C2000 MCU. Both the figures show the specific controller used in this case is TMS320F28002x series MCUs. [Figure 7](#) and [Figure 8](#) indicate all the interface signals needed for full control of this DC-DC converter using a F28002x MCU. The MCU controls each boost stage using three feedback signals and two PWM ([Figure 7](#)) or four PWM ([Figure 8](#)) outputs. The sensed signals are, panel output voltage (V_p), the boost output voltage (V_{bus}) and the total boost inductor currents (I_{in}). These sensed signals are used to implement the voltage and current control loops for the DC-DC stage.

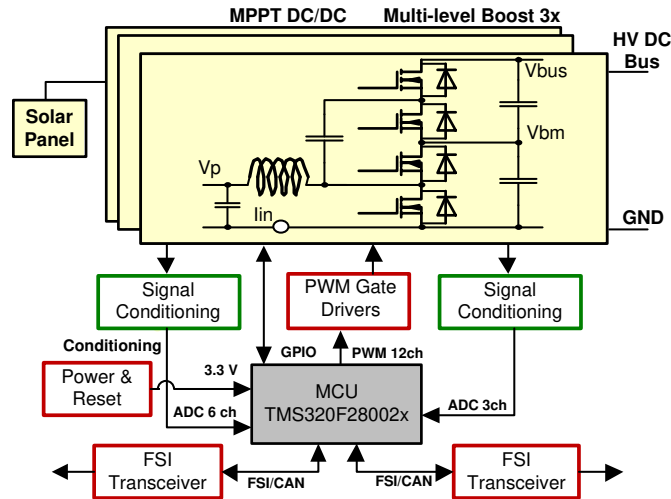


Figure 8. MPPT Multi-Level DC/DC Boost Control Using C2000 MCU

Figure 9 shows the boost converter control loops. This uses the current mode control. However, the goal is to control the PV panel output (V_p) that is the input to the DC-DC stage. This allows the PV panel (array) operates at its maximum power point at all time. Input voltage V_p is regulated by adjusting the input current I_{in} . A Maximum Power Point Tracking (MPPT) algorithm determines the set point (V_{p_ref}) for the PV panel voltage.

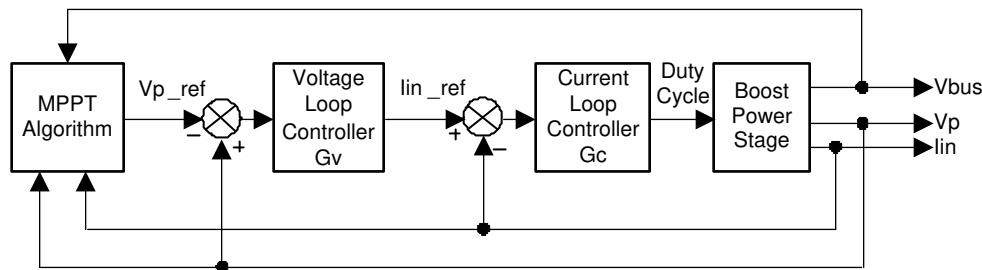


Figure 9. MPPT DC-DC Converter Control Loops

Table 1 shows the number of F28002x MCU needed to support different configurations of MPPT DC/DC boost stages shown in Figure 9. For example, to control 12 boost stages, shown in Figure 8, a total of four F28002x MCUs are needed. This is because 12 boost stages require 48 PWM and 36 ADC channels and the four F28002x MCUs provide 56 PWM and 64 ADC channels. Thus, the number of spare PWM and ADC channels for such a configuration will be, 8 and 28, respectively. This is also listed as the last two row entries in Table 1. The last two column entries in Table 1 also show the F28002x MCU requirements for controlling 16 and 24 MPPT DC/DC boost stages. For 16 MPPT stages, five F28002x MCUs are needed. For 24 MPPT stages, the number of F28002x MCUs needed will be 7.

Table 1. MPPT DC/DC Boost Stages vs Number of F28002x MCU

	MPPT-12 Boost Stages	MPPT-16 Boost Stages	MPPT-24 Boost Stages
# PWM channels needed	48	64	96
# ADC channels needed	36	48	72
#F28002x MCU needed	4	5	7
Spare PWM channels available for nBoosts configuration	8	6	2
Spare ADC channels available for nBoosts configuration	28	32	40

3.2 DC/AC Inverter Stage

This section shows two examples of DC/AC inverter topologies used in solar string inverter application. As shown in Figure 10, a single phase two-level DC/AC inverter comprises of a full bridge with four switches, followed by an output filter stage. An inductor capacitor (LCL) output filter is shown in the diagram. To regulate the current feeds into the grid, the C2000 MCU senses the voltages and current signals as indicated in the diagram and then runs the control algorithm to compute the PWM duty ratio for the four switches.

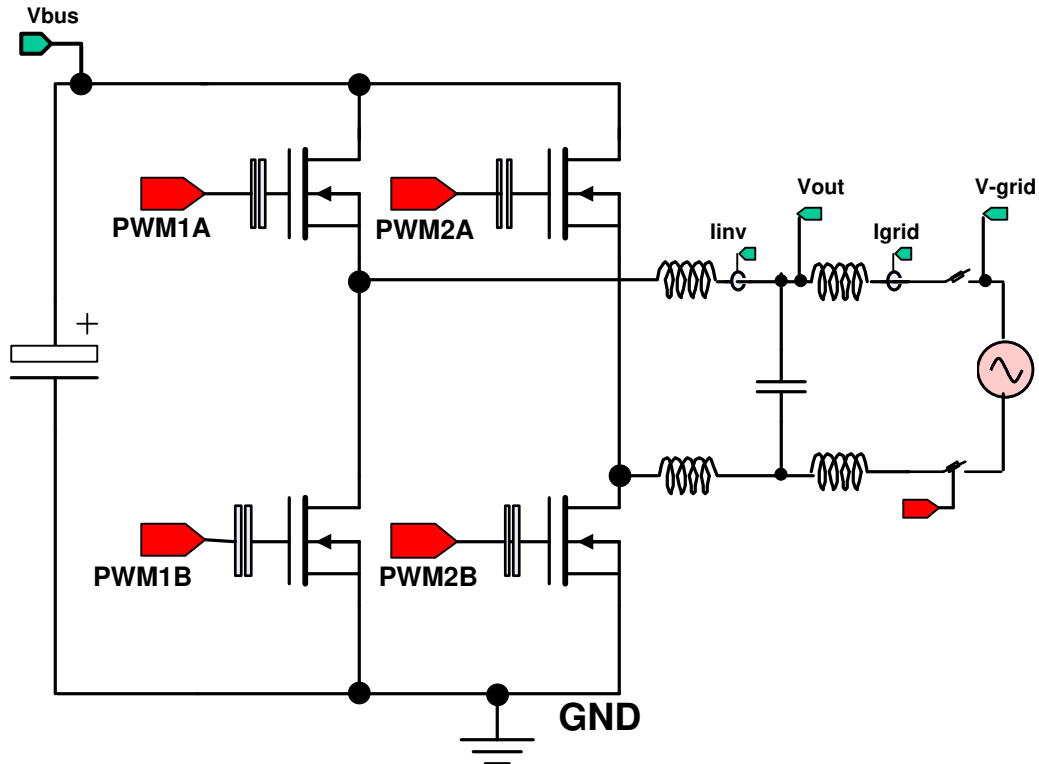


Figure 10. Single Phase DC/AC Topology Used in Solar String Inverter

For this kind of inverter each switching device blocks the full DC link voltage V_{bus} . Therefore for higher power output when the DC link voltage is pushed higher it puts an upper limit because of the switching device blocking voltage rating. Additionally higher DC link voltage means increased switching losses in the traditional MOSFET resulting in decreased efficiency. Because of these limitations at higher power two-level inverters are replaced by three-level inverters.

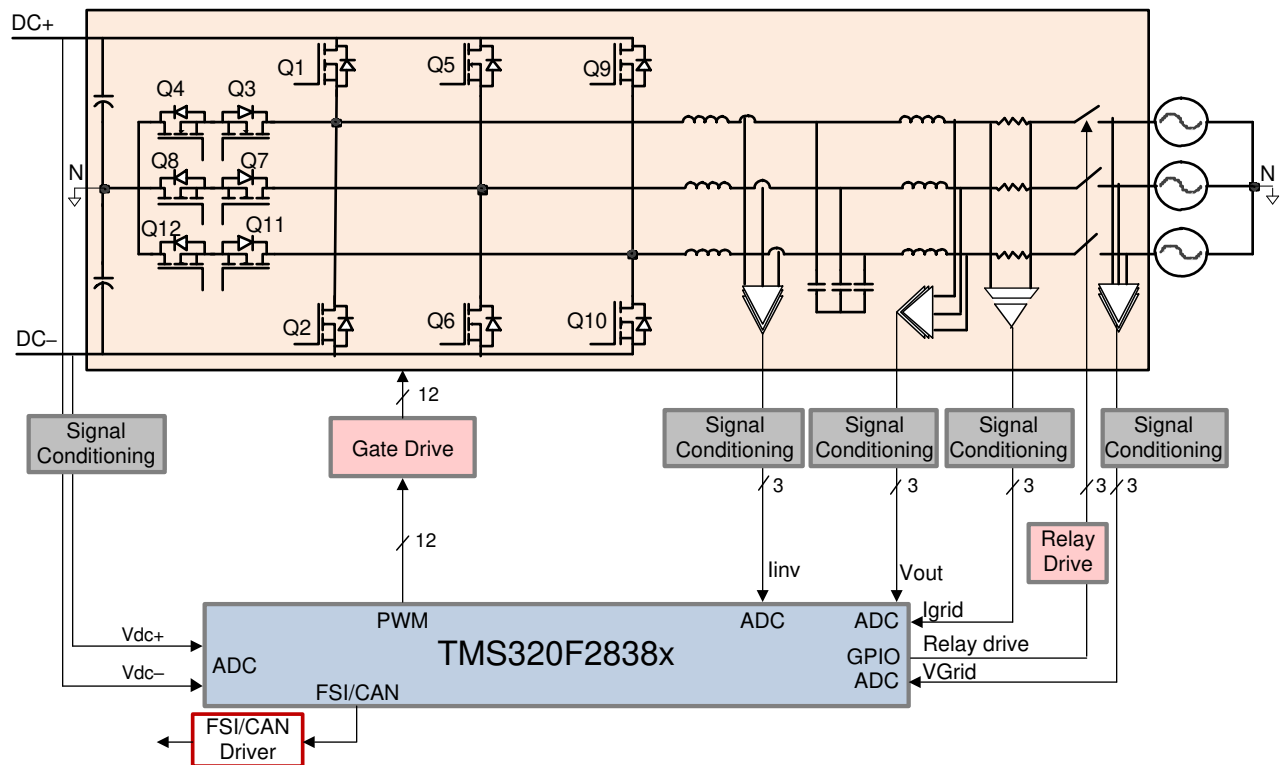


Figure 11. Three Phase 3-Level DC/AC Inverter Control Using F2838x MCU

One such three-level topology and its interface to C2000 MCU is shown in Figure 11. The controller used in this case is the TMS320F2838x series MCU. This figure shows a T-type three phase three-level inverter. Two back-to-back switching devices are inserted between the switch nodes and the neutral point of the DC link created by the bulk input capacitors. These two switching devices are placed in a common emitter configuration so that current flow can be controlled by controlling (on/off) one of the two switching devices. Here again, F2838x MCU senses the voltage and current signals as indicated in the diagram, runs the current control algorithm and finally computes the PWM duty ratio for all inverter switches.

4 C2000 Controller Configuration for DPCA DC/AC System

This section discusses different C2000 MCU configuration for distributed power control of the solar string inverter DC/AC system. Use of the fast communication link such that the FSI port in order to significantly increase the scalability of MCU resources (PWM, ADC and MIPs) and hence, implementing the DPCA system will also be discussed. Figure 12 illustrates the use of two different series of C2000 MCUs in order to implement DPCA for the solar string inverter system discussed before. As indicated in Figure 12 one F2838x series MCU is used for grid-tie inverter control and multiple F28002x series MCUs are used for MPPT DC/DC control. All the MCUs are then connected through the FSI port. This configuration will allow full flexibility and scalability in the design. For example as indicated in Table 1, one inverter system may require 12 MPPT DC/DC stages which can be implemented with four F28002x MCUs controlling the DC/DC stages and one F2838x MCU controlling the DC/AC stage. Then all the MCUs can be connected over the FSI ports. Now this can be very efficiently modified for another inverter system requiring 16 MPPT DC/DC stages just by adding one more F28002x in the system. The max number of F28002x MCUs that can be connected through FSI and the way the MCUs are connected in such system is further discussed in Section 5.

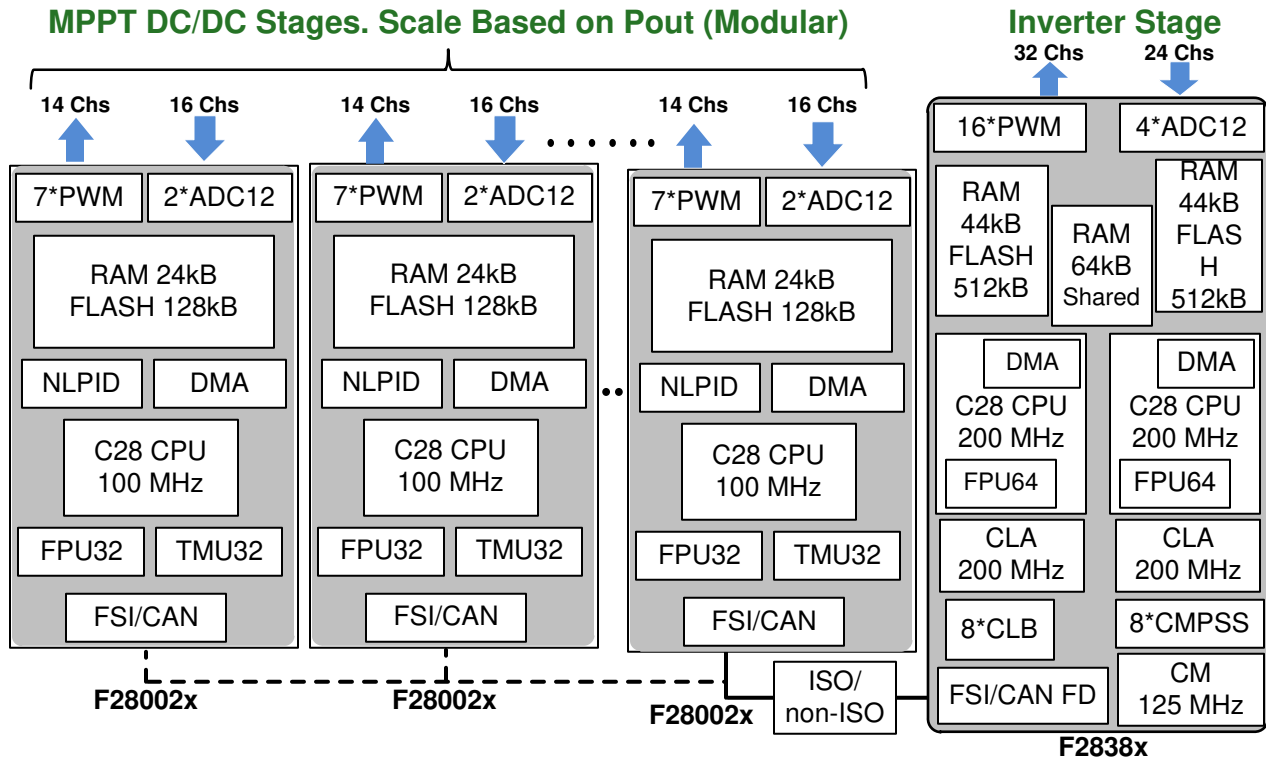


Figure 12. F28002x and F2838x MCU Configuration for DPCA Solar Inverter System

Based on the application requirements, the inverter stage controller in Figure 12 can also use F28004x series MCU, which is indicated in Figure 13. All the MCUs are then connected through the FSI port. Again, the maximum number of F28002x MCUs that can be connected through FSI and the way they are connected in such system is further discussed in Section 5.

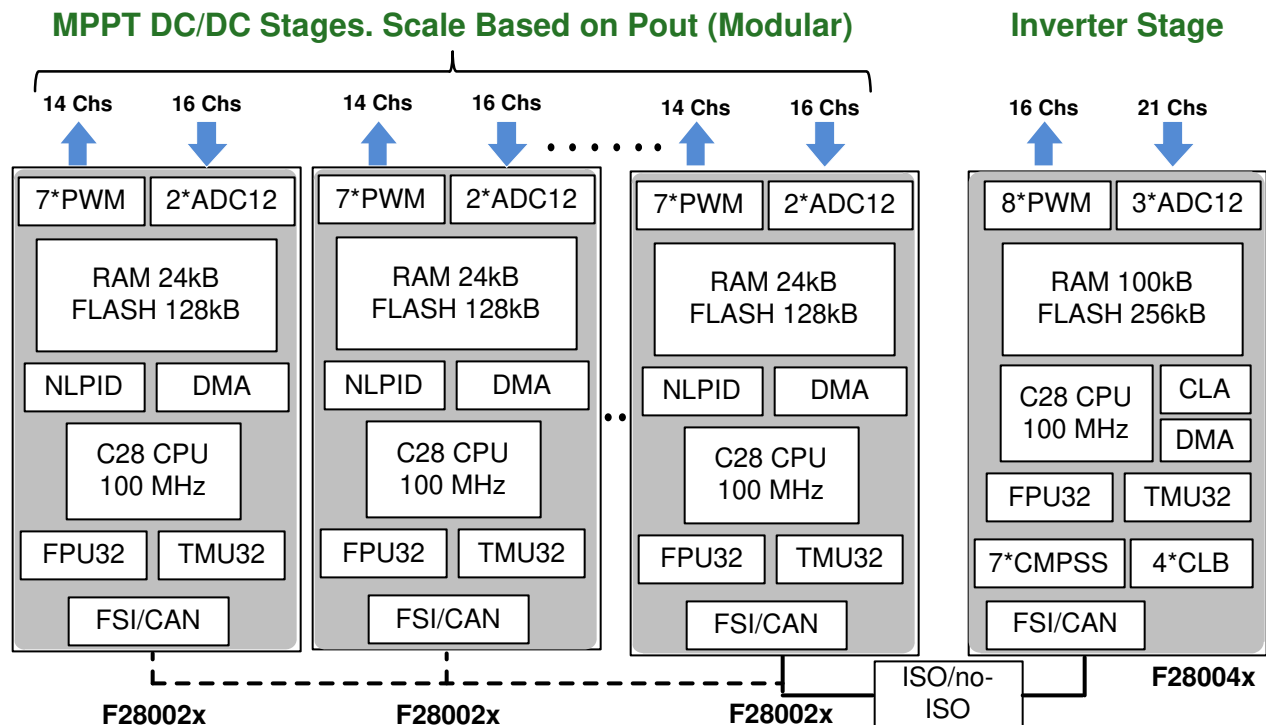


Figure 13. F28002x and F28004x MCU Configuration for DPCA Solar Inverter System

If the MPPT DC/DC stages require more peripheral resources, then these can be controlled by F28004x series MCUs with one F2838x MCU controlling the inverter stage, which is illustrated in Figure 14.

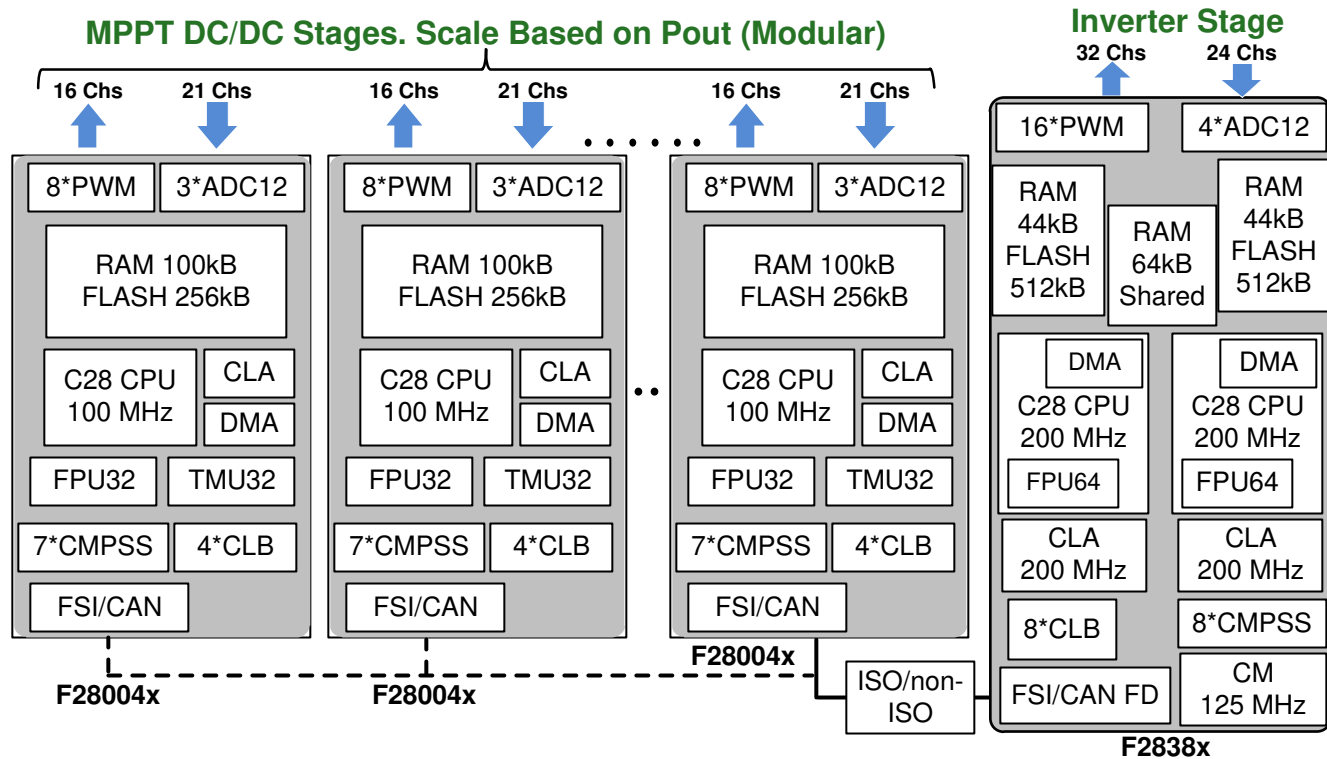


Figure 14. F28004x and F2838x MCU Configuration for DPCA Solar Inverter System

5 Communication Interface – FSI for DPCA DC/AC System

The Fast Serial Interface (FSI) module is a serial communication peripheral capable of reliable high-speed communication across isolation devices using only a few signals. The FSI consists of independent transmitter (FSITX) and receiver (FSIRX) cores. The FSITX and FSIRX modules are configured and operated independently. The FSI is designed to ensure data robustness across many system conditions such as chip-to-chip as well as board-to-board across an isolation barrier. Payload integrity checks such as CRC, start- and end-of-frame patterns, and user-defined tags, are automatically encoded before transmission and then verified after receipt without additional CPU interaction. Line breaks can be detected using periodic low latency transmissions, all managed and monitored by hardware. The FSI is also tightly integrated with other control peripherals on the device. With embedded data robustness checks, data-link integrity checks, skew compensation, and integration with control peripherals, the FSI can enable high-speed, robust communication in any distributed system.

There are multiple ways in which various devices (MCUs) in a distributed power control architecture can be interfaced using FSI. The next section presents two FSI configurations that are applicable to this distributed power control architecture.

5.1 FSI Star Connection

In the star network connection shown in Figure 15, all slave devices connect to a single master device. The master broadcasts a message via its FSITX port, which in turn is connected to all FSIRX ports of all slave devices. All the slaves respond via their FSITX ports, each of which are connected to different FSIRX ports on the master device.

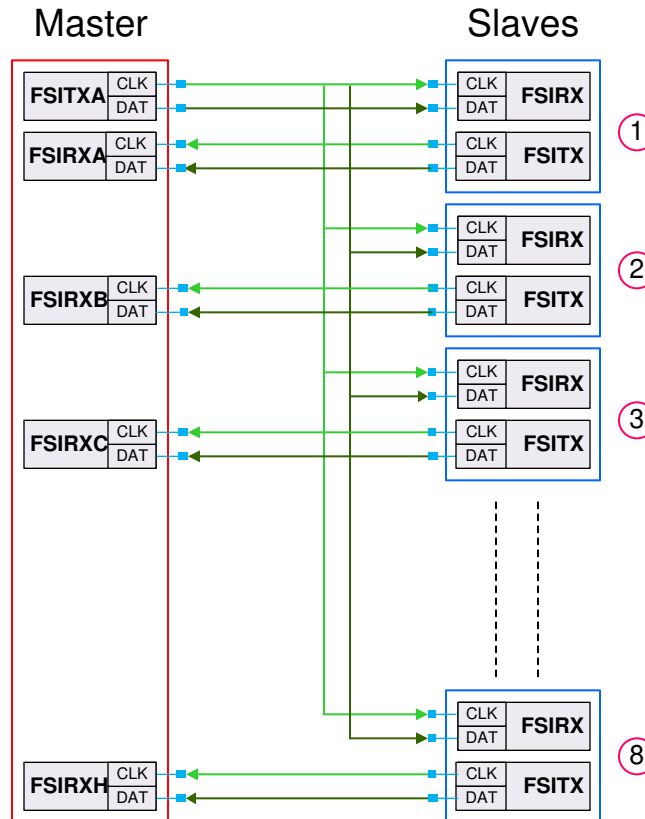


Figure 15. Devices (MCUs) Connected in Star Topology

F2838x MCU supports 8 FSIRX ports and, hence, this topology can work up to 8 slave devices in the DPCA system. Thus, in a solar string inverter application one F2838x can control the DC/AC inverter stage as a master device and then 8 F28002x or F28004x MCUs, connected through FSI as slave devices, can be used for MPPT DC/DC control. In Table 1, it was calculated that a total of 7 F28002x MCUs are needed to control 24 MPPT DC/DC boost stages. Thus, the star connected configuration of F28002x MCU will allow control of 24 MPPT DC/DC boost stages in string inverter application with F2838x MCU controlling the DC/AC inverter stage as the master device.

F28004x MCU supports one FSI port and hence this star connected topology can work up to one slave devices in the DPCA system. Therefore, for the DPCA inverter system shown in Figure 13, there can only one F28004x MCU connected to one F28002x MCU when they are connected in a star configuration. However, the same system can be implemented using a different FSI configuration with multiple F28002x slave devices. This configuration is discussed in next section.

Some advantages of star topology are: easy point-to-point connection from slave to master and minimal latency in the communication as master broadcasts the message to all slaves and slaves directly respond back to master. In this configuration, the MPPT DC/DC MCU can send its voltage and current information to DC/AC MCU and offload some of the slower control tasks to that MCU. Such control tasks may include running the MPPT algorithm or calculating the panel voltage control loop output. DC/AC MCU can also calculate some system parameters such as, the total system power, MPPT voltage (for each DC/DC), and so forth, and implement system level control. This can also be used for rapid shutdown control where the inverter MCU sends the heartbeat signal to all MPPT DC/DC MCUs. As long as the DC/DC MCUs keep receiving the heartbeat they operate as normal. If they do not receive the heartbeat signal in the allocated amount of time they go into shut down mode. Star topology may result a higher cost to implementation depending on interconnect and isolation requirements across master and multiple slaves. The support is also limited to a maximum of 8 slave nodes with the F2838x device.

5.2 FSI Daisy Chain Connection

In this daisy chain network topology as shown in Figure 16 and Figure 17, multiple devices are wired together in a ring topology. Figure 16 shows the connection with 1 data line and Figure 17 shows the same for 2 data lines. Message from master device goes through series of slave devices connected serially. This topology does not pose any limit on the number of devices in the network and amends itself to simple wiring of various nodes. Due to the nature of a daisy-chain connection, data will need to pass through N devices for the transmission before it reaches the last device adding to latency.

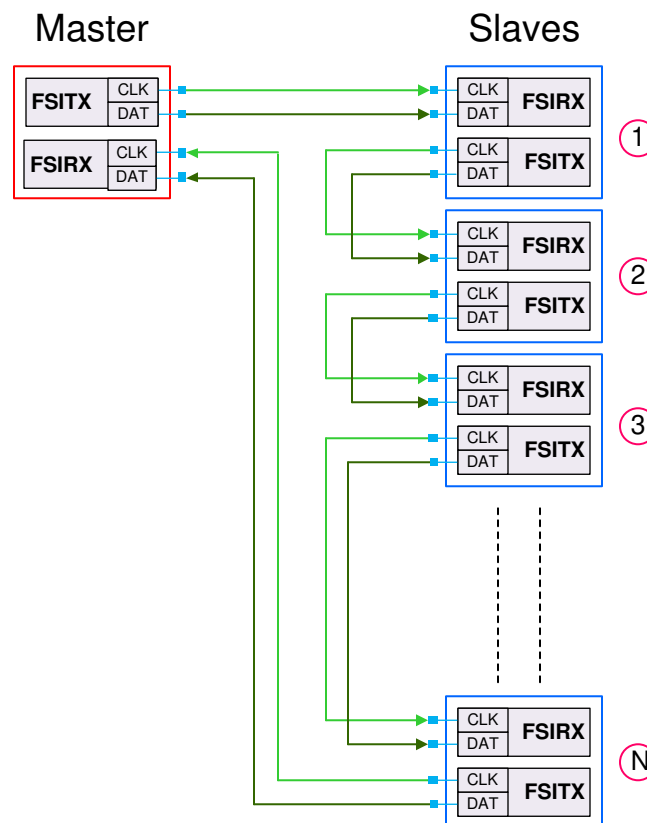


Figure 16. Devices (MCUs) Connected in Daisy Chain Topology With 1 Data Line

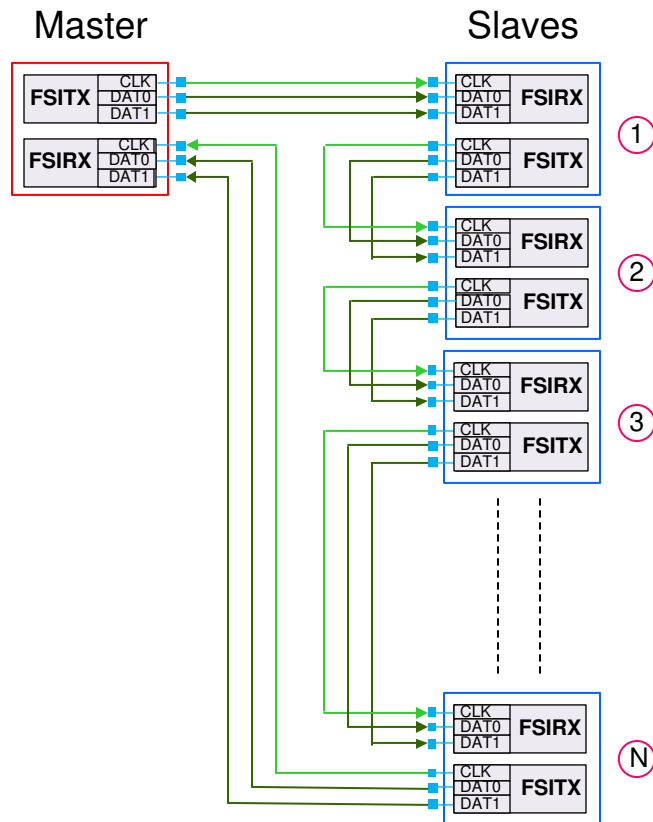


Figure 17. Devices (MCUs) Connected in Daisy Chain Topology With 2 Data Lines

In [Table 1](#), it was calculated that a total of seven F28002x MCUs are needed to control 24 MPPT DC/DC boost stages. Therefore, to control 24 MPPT DC/DC boost stages using a daisy chain configuration the transmission delay of all 7 MCUs need to be calculated when the master device (the DC/AC inverter MCU), attempts to communicate with the 7th DC/DC MCU in the chain. This will be the worst case delay in the chain.

For the DPCA inverter system illustrated in [Figure 13](#), the master MCU (F28004x) has only one FSI port. Therefore, in this case, the only way more than one F28002x slave MCUs can be connected in the FSI network is through daisy chain connection.

5.3 FSI Frame

The FSI module transmits and receives information in frames. The shortest frame is 16 bits long (without counting the preamble and postamble clock edges). The basic frame structure for 16-bit data is shown in Table 2. Table 3 shows the same for 128-bit data. In the normal mode of transmission, there are four preamble clock edges before the start of the frame and 4 clock edges after the frame. Data is transmitted on both edges of the clock. Each field of the frame (like the Start-of-Frame, Frame type, and so forth) will be transmitted with the most significant bit sent first.

Table 2. Data Frame With 1 Word (16-bits) of Data

IDLE State	Preamble	Start of Frame	Frame Type	User Defined Data	Data Words	CRC Byte	Frame Tag	End of Frame	Post Frame Clocks	IDLE
	4 clock edges	1001	0100	8 bits	16 bits	8 bits	4 bits	0110	4 clock edges	

Table 3. Data Frame With 1 Word (16-bits) of Data

IDLE State	Preamble	Start of Frame	Frame Type	User Defined Data	Data Words	CRC Byte	Frame Tag	End of Frame	Post Frame Clocks	IDLE
	4 clock edges	1001	0100	8 bits	128 bits	8 bits	4 bits	0110	4 clock edges	

5.4 FSI Transmission Latencies

Table 4 lists the transmission latencies for a FSI frame across 2 adjacent nodes. The transmission times for 1 data line are shown in second column and those for the 2 data line mode are shown in the third column.

Table 4. Transmission Times for a FSI Frame Across Two adjacent Nodes

Data Size (Words) Word = 16 Bits	Transmission Time 1 Data Line (μ Sec)	Transmission Time 2 Data Lines (μ Sec)	Transmission Time at Each Slave Mode (μ Sec)
1	0.56	0.4	2
2	0.72	0.48	2
3	0.88	0.56	2
4	1.04	0.64	2
5	1.2	0.72	2
6	1.36	0.8	2
7	1.52	0.88	2
8	1.68	0.96	2

In addition to the above transmission delay, there may be an additional approximately 2 μ s delay at each slave for receiving the data and re-transmitting the same to the adjacent slave. This is indicated in the fourth column of Table 4. This delay time is based on the current software forwarding scheme.

Now, let us consider the example of distributed power control architecture (DPCA) where 24 MPPT DC/DC boost stages, controlled by seven F28002x MCUs, are connected in a daisy chain configuration with 1 data line, with the master F2838x MCU controlling the DC/AC inverter stage. Assume that each MPPT MCU tries to send two 32-bit data variables (64-bit data), such as the MPPT voltage and current information, to the master MCU over FSI.

The worst case transmission delay in this example will be between the master MCU and the 7th MPPT DC/DC MCU. This is the one way transmission delay where data goes from the master MCU to the last DC/DC MCU in the chain or the other way.

For the 64-bit data it will take 1.04 μS for transmission between two adjacent nodes when one data line is used. In addition to this there will be approximately 2 μS delay at each MCU for forwarding the data along the chain. Therefore, the total transmission delay for data from master MCU reaching the 7th DC/DC MCU, or the other way, through the single data line will be, $7 \times 1.04 \mu\text{S} + 6 \times 2 \mu\text{S} = 19.28 \mu\text{S}$.

However, the total loop delay (when data goes through the complete daisy chain loop) in transmitting and receiving data between the master MCU and any of the slave DC/DC MCUs will be the same. This delay, for one data line is, $8 \times 1.04 \mu\text{S} + 7 \times 2 \mu\text{S} = 22.32 \mu\text{S}$. This means that, for this specific example of string inverter system with DPCA, any calculation done in the master MCU involving these two data variables related to any of the slave MCUs in the chain can run at a maximum frequency of about 45kHz when one data line is used. This sets the limit for the fastest calculation rate that can be off loaded to the master MCU from any of the slave MCUs in the chain or the other way. For 2 data lines the same loop delay is, $8 \times 0.64 \mu\text{S} + 7 \times 2 \mu\text{S} = 19.12 \mu\text{S}$. Therefore, in this case the calculation off-loaded from one MCU to the other can run at a maximum frequency of about 52.3 kHz.

6 Summary

DPA approach provides many advantages for power conversion solutions that require a wide range of output power and output voltages. This white paper presents the application of C2000 MCUs in implementing control of such DPA systems. This approach essentially implements a DPCA system using multiple C2000 MCUs, taking full advantage of its CPU, flexible control peripherals and the fast serial interface (FSI). The document starts with an overview of C2000 MCU based DPCA for different power conversion systems. Then, a case study of solar string inverter DPCA system has been presented in detail with different types for FSI network connections. Finally, an example calculation on FSI transmission and loop delay for this system has been presented for the system designers as a guideline, allowing them to distribute appropriate tasks between multiple MCUs in the system.

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